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AND QUALITY CONTROL

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IRE TRANSACTIONS ®

on Reliability and Quality Control

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Manufacture and Control of High Frequency Transistors for Consumer Products

C. B. TAGUE,† member IRE, and H. C. BARTELS,† member, IRE

Summary—The philosophy of manufacturing transistors on an automatic line optimized for a particular high frequency type is reviewed. The method of optimizing for different types and the process controls used to monitor these procedures are analyzed.

The concept of defining high frequency characteristics through functional tests rather than by traditional parameters and some of the problems encountered with this approach are discussed.

Results of sampling tests for life and electrical characteristics are reviewed. Field data, both consumer production line and in use failure rates, are given.

A few years ago, the entertainment market was evaluated by many transistor manufacturers as having considerable future potential but at the time was no more than a means of disposing of transistors which failed to meet the requirements of a more lucrative industrial market. With the advent of the Philco automatic production line, however, the feasibility of making transistors specifically for consumer products was recognized and a complete line of MADT transistors for high frequency consumer applications has evolved. This line covers a range of amplifiers, converters, reflex amplifiers, oscillators and mixer units from the 262-Kc IF amplifier in home radio to the 257-Mc oscillator of the TV tuner.

This paper will attempt to describe briefly the Philco MADT process and to emphasize the controls both inherent in and applied to the process which assure the complete interchangeability within a type which is characteristic of MADT transistors.

The MADT process begins with the control of dopant included in the germanium when the ingot is drawn. Because the desired final resistivity is relatively high, comparatively little dopant is used and so must be closely controlled. The range of resistivity of a lot of blanks ready for diffusion will be one- to two-ohm centimeters with the average resistivity being about 30-ohm centimeters. The blanks are diffused with arsenic to depths, concentrations and gradients consistent with the particular type of transistor in which it will be used. We shall see later how control of the diffusion process plays an important role in optimizing an automatic manufacturing line to produce the desired transistor type.

With the completion of the diffusion process, the blank is ready to start through the automatic line which will mold it into a transistor.

The diffused blank is mounted on a tab which has been inserted into a Stainless Steel Carrier. The carrier has been machined to near Jo block accuracy and will serve to locate the embryo transistor in each of the processes through which it must progress.

On the Etch-Plate machine, a collector pit is electrolytically etched into one side of the blank and an emitter pit into the other. The most important feature of the etching process is that the etching is so closely controlled that the thickness of the web between the two flat, smooth concentric pits can be controlled to extremely fine tolerances —in the range of 0.01 mils or about 10 millionths of an inch. This web thickness, or base width, is another of the design dimensions which will eventually determine the electrical performance of the transistor. Because it can be so closely controlled in the precision-etch process, the electrical characteristics which are determined by it will also be tightly distributed.

The next station on the etch-plate machine plates a tiny dot of cadmium concentrically into each of the etched pits. The diameter and configuration of these dots must be controlled to extremely tight tolerances since the area of the plated dots will determine the area of the emitter and collector electrodes. As we shall see later, these areas are one of the principal determinants of interelectrode capacitances which are so important in controlling the performance of the transistor at high frequencies.

To monitor the efficiency of the etching process, the test station on the end of the etch-plate machine contacts the plated dots and measures the base-emitter and base-collector diodes which have been formed by the plated dots. The results of these tests are plotted on a recorder on the machine and determine whether or not the process is in control up to this point.

The carrier holding the etched and plated blank

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is now transferred to the shuffleboard machine on which the emitter and collector leads will be attached and on which the final surface treatment will be started.

The first operation on the shuffleboard is attachment of the emitter lead or whisker. The whisker is prepared by electrolytically plating a pellet of tin cadmium solder on the end of the wire which is fed from a spool. The whisker is cut and formed and the carrier containing the etched and plated blank is brought into position. A voltage applied to the jaws holding the whisker melts the solder which flows onto the plated dot.

The emitter solder contains a small amount of gallium which actually dissolves some germanium during the soldering process. As the solder cools, the germanium recrystalizes out, leaving a highly doped P-type region immediately beneath the emitter electrode. This is the Micro-alloy process, and its control is one of the most critical phases in MADT manufacture.

The shuffleboard then turns the carrier over and the collector whisker is attached in the same way. The transistor is then rinsed with mild acetic acid and again tested to determine the efficiency of the Micro-alloying and lead attaching operations. Both diodes are again checked, as well as D.C. Beta, which is an indicator of the injection efficiency of the transistor, and thus an indicator of the degree of Micro-alloying which has been accomplished. The results of these tests again determine that the process is in control.

The next station is electrolytic surface treatment with caustic followed by rinsing in hot 20-megohm water to remove the caustic from the surface. The water is removed with clean filtered air and the transistor is ready for removal from the carrier and assembly to the header.

After assembly, the transistors are vacuum baked at elevated temperature to remove residual moisture and complete the surface treatment. They are unloaded from the oven into a dry box where the ambient is filtered air which has been dried to a moisture content of less than five parts per million. The transistor is encapsulated in this atmosphere. After a stabilization bake at elevated temperatures, the units are ready for final testing for electrical parameters.

One of the outstanding features of the MADT automatic production line is that it can be optimized to manufacture a particular type or family of transistors. Whether the application is for a high-speed switch in a computer, an IF amplifier in home or auto radio, or an RF amplifier in a TV tuner, there is a specific geometry for the transistor which will optimize its performance in the application. For a switch, as an example, we are most interested in performance at low voltage, while in the TV tuner we are more interested in gain and noise figure at 200 megacycles. It is a fact that the transistor geometry best suited to low-voltage switch applications is not the best geometry for a high-frequency amplifier.

Let us examine some of the changes in transistor geometry which we have mentioned earlier and see how they affect the electrical performance of the transistor, and how, by building in the proper combination of these design parameters, we can increase the interchangeability and reliability of the product for a particular transistor application.

First, of course, is the diffusion gradient. This defines the built-in field which will determine the time required for an injected hole to travel from the point of injection to the edge of the gradient. There is an optimum logarithmic curve for this gradient, but since other factors, such as injection efficiency of the emitter at low voltages are sometimes more important, the optimum cannot always be used. It becomes necessary, then, to determine how much to compromise the optimum profile in order to achieve optimum transistor operation.

The diffusion profile will also determine the maximum emitter-to-base voltage which can be applied to the transistor. The resistivity of the germanium at the point in the profile at which the emitter electrode is placed will affect both the injection efficiency and the maximum reverse voltage of the emitter diode.

Placement of the emitter electrode in the profile presents another compromise which again must be resolved so that transistor operation in the application is optimized.

For low base input impedance, it is desirable to place the emitter as close as possible to the surface—that is, on a relatively low resistivity. However, in order to increase the maximum allowable base-emitter voltage, minimize input capacitance, and obtain maximum possible injection efficiency, it is desirable to place the emitter as far into the profile as possible—that is, on relatively high resistivity material.

The resistivity of the material in the center of the blank, the bulk resistivity, also affects the electrical performance of the transistor and may be varied to obtain a desirable feature for a particular socket, such as control of gain fall-off with voltage for AGC applications. This resistivity, along with the base width, will determine the maximum allowable collector-to-base voltage.

The diameters and the flatness of the etched pits, and the diameter of the electrodes are examples of other geometric dimensions which may be varied to control the interelectrode impedances and capacitances which determine the eventual

electrical characteristics of the finished transistor.

The details of the geometry changes outlined above are unimportant to the circuit designer, so long as the finished product meets his requirements. It is extremely important, however, that each transistor of a particular type be the same, within close tolerances, as any other transistor of the same type, and that the performance of that type in his circuit be the best performance obtainable.

It can be seen, then, that with all the variables which must be controlled in the process, that it is no longer possible to test performance into the output of a manufacturing line. As circuits for consumer products become more and more sophisticated, it becomes more and more important that circuit performance be built into the transistors during the manufacturing process, and that the process be capable of being optimized for each of the hundreds of different applications which are evolving in this fast growing field.

Assuming that all these factors which affect the performance of the transistor can be controlled, how do we go about defining the transistor which will best do the job which needs to be done? The conventional small signal parameters are of little help. We can define h_{ib} and h_{ob} at 1 Kc, but these will have little relationship to the input or output impedance of a TV mixer unit when the channels are switched suddenly from 2 to 13.

It is possible to define a high-frequency amplifier using parameters such as high-frequency input and output impedances and capacitances, gainbandwidth product (f_t), and $R_b' C_c$, but because the effects of many of these are overlapping, it would be economically unfeasible to attempt to place limits on each of them to define a good transistor.

It is not necessary to apply limits to each of a dozen or so parameters to insure optimum operation in the application. For the majority of sockets, limits on power gain, bandwidth and noise figure tested in a fixed matched and fixed neutralized circuit at the frequency at which the unit will be used will be sufficient. With these characteristics defined and well specified, no transistor which has not been optimized for the particular operation involved will fall within the limits specified. It is possible, in this type of circuit, to shift output capacitance, for instance, so that the circuit would be regenerative. This would appear to have improved the power gain level. In the same circuit, however, the bandwidth will go down and the noise figure up and it will not be very long before the line engineer who decided to improve his gain level by adjusting his output capacitance will be convinced that the specs were right all along.

Control of quality begins with the raw materials and must be maintained through control over each process that can affect the quality or reliability of the finished product. At incoming inspection, all parts are sampled for those dimensions or other characteristics which affect the final device. The composition of the various raw materials is analyzed by the chemical lab for conformity to specification. Spectrographic analysis is used for sampling critical materials, such as plating solutions, used in the device manufacture where the amount of trace impurities or additives may have a decisive effect on the device characteristics.

During the entire manufacturing process, statistical quality control methods are used to control, at each step, the geometry, the materials and the workmanship that goes into the MADT transistor coming off the line. It is through the rapid feedback obtainable from a good control system in an automatic line that a uniform and uniformly reliable transistor is obtained.

So far, we have been concerned almost exclusively with the manufacturing process and its control. How does this tie in with reliability? It is our feeling that reliability must be built into the product. To build it in, we utilize feedback from the user to improve test and evaluation methods, surveillance of reliability and quality control acceptance to improve device designs and manufacturing controls, and, of course, in process controls, to maintain the necessary product uniformity.

Reliability can be defined as success in use, i.e., the measure of the product's ability to perform, over a period of time, the specific function for which it was designed and manufactured. It is entirely possible for anything, whether it is a transistor or safety pin, to have a fantastically low failure rate when used for the purpose for which it was made, and to fail almost instantaneously when used incorrectly.

We must, before we can release our product to customers, evaluate our product in terms of reliability and quality to insure its ability to perform the specific function for which it was designed and manufactured. This evaluation is the measure of our ability to build in the performance necessary for satisfactory operation in the application.

To measure the effectiveness of the line controls and as a part of over-all product control, each lot of transistors is evaluated prior to release for shipment to the consumer. This evaluation includes sampling tests to all published parameters, additional design tests for acceptance of other variables that may affect product quality

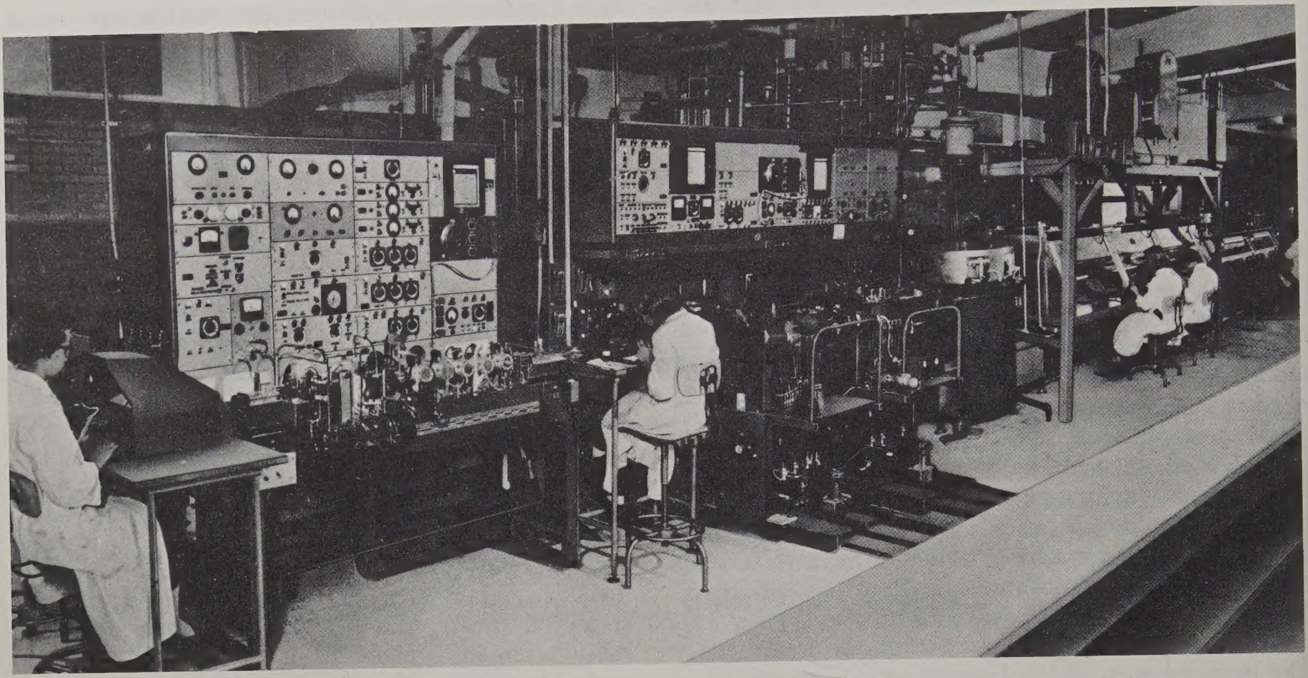

Fig. 1. Fast* Line

*Fast Automatic Semiconductor Transfer

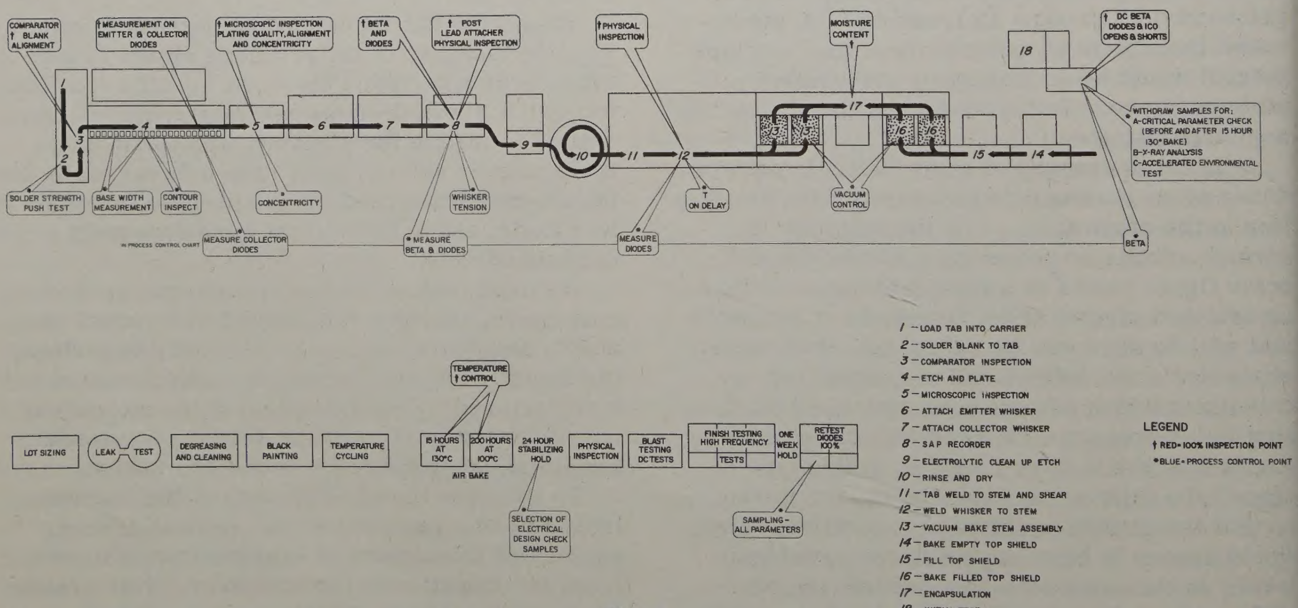

Fig. 2.

and reliability, and life testing at the maximum device rating. It is here that we not only measure the finished product's quality and ultimate acceptance, but also gain valuable design control information for feedback into the line.

The chart in Fig. 3 shows a summary of the

QUALITY CONTROL SAMPLING
FAT Line RF & IF Types

TESTS	AQL	Σn	Σr	Process Av
Group I Visual & Mechanical	1	17300	9	0.05
Group II BVCBO, ICBO IEBO, hFE	1.0	12315	68	0.55
Group III ft, hFE, Cob $r_b^1C_c$, ICES	2.5	1960	12	0.60
Group IV PO, PG BW	4.0	1695	23	1.4

Fig. 3.

Group A, or electrical, sampling results of one FAT line over a period of one year on a typical production run.

The tests are arranged in the chart according to the AQL grouping we normally follow and the results of the sampling are recorded by group. Data are included for all the types made on the line since the run was not continuous for one type but was varied to meet demand; therefore, all of the tests listed were not necessarily required or performed on each lot.

In Group I, we list as inoperatives those units that show little or no transistor action, shorts and opens. The visual and mechanical rejects included are only the major items such as missing leads, open welds and major poor workmanship items. The other three groups cover the various electrical tests and are as defined in the individual test specifications.

All of the test results tabulated are for the first sample of the lot, taken directly from the completed transistors from the line, so the process average tabulated in the chart can be taken as the true process average for the production line. The quality reaching the customer is a measure better than this by the 100 per cent retest of those lots falling outside the control limits for acceptance. The conclusion may be drawn from this chart that this line is meeting its requirements with a high degree of confidence.

It is expected that the output of a line optimized for a specific type would produce a more uniform version of that type. Fig. 4 shows the distribution

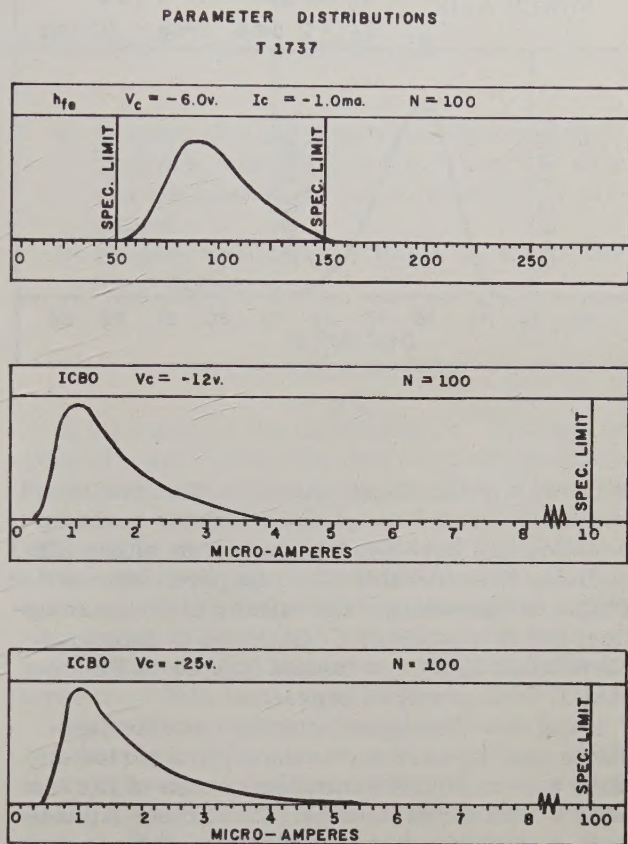

Fig. 4.

of some of the parameters measured on a video-driver transistor for TV. This distribution reflects the ability to control the characteristics of the transistor within the published limits. The ICBO distributions, both high and low voltage, show good control and also indicate the conservative rating for this parameter. The power gain distribution of Fig. 5 for an RF unit for TV tuners shows how effectively the controls described earlier in this paper maintain final product uniformity.

Life test samples are taken weekly on the output of each line and are performed at the maximum junction temperature rating, usually for a period of one thousand hours. Criteria for device failure during life usually reflect the philosophy that BVCBO must remain above the maximum rating of the device, ICBO may not increase beyond double the initial limit, and hFE must not go below half of the initial limit.

These parameters were chosen because it is

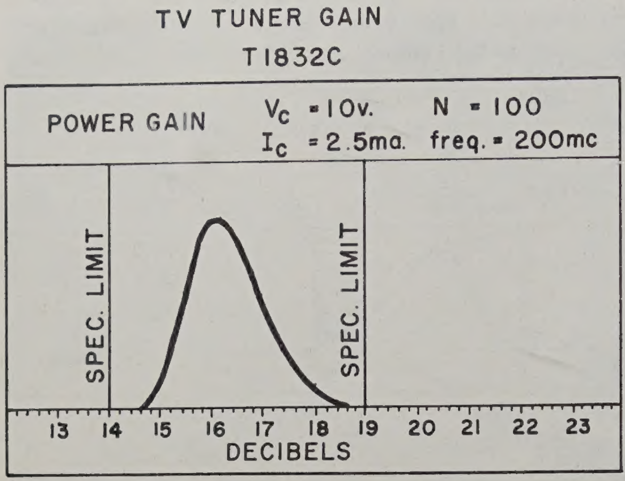

Fig. 5.

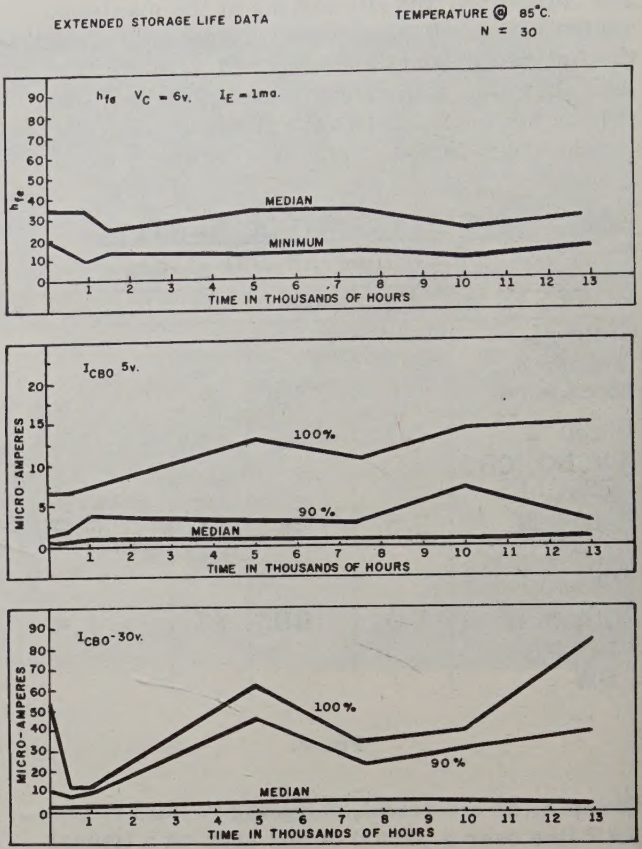

Fig. 6.

believed any significant change in parameters affecting the usefulness of the transistor in the application will have a marked effect on either ICBO or Beta. Considerable effort has been expended at Philco to demonstrate the validity of this assumption, and in a paper by C. Gray and C. Simmons, correlation data for a limited number of Philco MADT devices will be presented.

From one-line manufacturing units for television use, we have accumulated, in a period of about a year, 571,000 transistor hours of life test at 85°C with seven failures. Six of these failures were degradation failures where the devices went outside electrical limits with only one failure being of catastrophic nature. Assuming none of these failures was due to operator or test equipment malfunction, we can estimate a mean time to failure for this device of 95,000 hours for degradation failures and 571,000 hours for catastrophic failures. This is a failure rate of 1.05 per cent and 0.175 per cent per thousand hours, respectively.

In use, with normal design safety factors, the device would probably never be exposed to the stress level at which our life tests are performed. Using the accepted derating factor of doubling life for every ten degrees reduction in junction temperature, we can, therefore, calculate mean time between failures of three quarters of a million hours for degradation failures and nearly five million hours for catastrophic failures for this device run at half its rating.

Some of the life tests are continued beyond one thousand hours to gain information on extended life performance of the devices. Thirty units of one of the early types have now reached 13,000 hours. Fig. 6 shows a plot of three of the parameters against time. These curves show that these units have remained stable within limits for a period of a year and a half at maximum rating.

The only real proof of the reliability of a device is in actual use. Data are available for a production run of Philco Safari portable television sets using transistors delivered from this line for use in RF and IF sockets.

Warranty figures from this run are now available for approximately 90,000 transistors from this line in use for a year in the field. There have been 19 rejects in the field due directly to failure of one of these transistors, indicating a reject rate of .021 per cent per year in actual use.

Data are also available on life test runs of these sets, at Philco, where we have recorded 216,000 FAT line transistor hours with no set malfunction attributable to a transistor.

The basic philosophy that this performance data confirms, then, is that optimization of the transistor in its application, as a result of optimization of the manufacturing process to produce a transistor for that particular application, is the key to reliable performance in the application.

Some Aspects of Satellite and Space Probe Reliability

T. W. GROSS,† member IRE, and H. C. WERNER,† senior member IRE

Summary—It is becoming a recognized fact that many of the electronic piece parts used in present day ballistic missile and space probes are inadequate for the long-life space programs of the near future. Realization of the major differences of life and reliability requirements resulting from short and long term exposures to the space environment has led to a four point plan for the establishment of an acceptable class of parts that will meet the more rigid demands. Presented here are the plan and some of the preliminary results obtained to date.

INTRODUCTION

In assisting the design effort in the selection of a satisfactory class of electronic piece parts, i.e., resistor, relay, diode, etc., for use in short-life space probes, we were readily aware that the existing parts being used in ballistic missiles were satisfactory. However, parallel activities by LMSD in creation of long life vehicles accentuated the need for stability in the long term behavior of parts which were subjected to high vacuum and varied electromagnetic and corpuscular radiation. In addition to these environments the parts must be protected from the continual temperature cycling that the vehicle experiences. Place upon these parts another requirement—that of withstanding many of the static and dynamic conditions of the ballistic missile—and the fact stands out that we are looking for parts with "super" characteristics.

Since LMSD cannot use the "wait and see" approach to determine whether available parts meet flight test objectives, it has embarked upon a plan which, for brevity, can be reduced to the following points:

1) Establish an active center for the collection and utilization of existing data.
2) Conduct evaluation and development programs to complement existing data and fulfill additional requirements to derive an acceptable class of parts.
3) Prepare high reliability procurement specifications based on data listed above to ensure that adequate parts can be repetitively purchased.
4) Prepare application criteria for use by design engineers.

DATA COLLECTION

In February, 1959, LMSD Satellite Systems organized a sub-contractor data exchange program. Since its origin, several hundred reports have been exchanged between members and a sound base of information now exists. In addition, LMSD receives data from the Polaris and the NOL Corona exchange, the Battelle ECRC program, informal interchange among NASA and ballistic missile manufacturers, and is now a participant in the Interservice Data Exchange Program (IDEP).

Data collected from these sources are being summarized in the form of a master chart. This chart reflects not only voids and areas where additional testing is needed, but is also an aid in preventing duplication of testing and the testing of unacceptable parts. However, it should be pointed out that we are not waiting until the testing from other programs is completed. Our program has immediate schedules and at this stage in our development, we cannot be completely dependent on future data from other sources.

We do intend to maintain close liaison with and hope to derive benefits from programs such as Minuteman, and in no instances will there be known duplication of effort. It also must be emphasized that the Satellite program has requirements and objectives that differ enough from other programs to require different test objectives.

EVALUATION PROGRAM

Tantalum Capacitors: The use of a great many capacitive elements in the satellite systems required that units with high capacitance-to-volume ratios be utilized because of size and weight requirements. The relatively new foil and solid tantalum capacitors prove ideal in this respect;

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however, there exist very little data demonstrating acceptable failure rates. There were a considerable number of problems with the solid tantalums when they were first introduced and foil tantalums were questionable because of their necessity for outgassing. Use in an unpressurized satellite would possibly result in the complete loss of electrolyte, critically affecting the units' capacitance value.

Four hundred and eighty units, consisting of eight types, were selected and set up in a sequence of test that simulates the environmental sequence experienced by a satellite. The test design will provide the data necessary to determine the effects of each individual environment as well as the cumulative effects of a series of environments. Further details on the design will not be elaborated upon now, but will be furnished to interested parties upon request. [1]

With approximately 45 per cent of the testing completed and with life tests soon to begin, the following results are of interest:

1) During initial measurements, one type of solid tantalum capacitor was eliminated from further testing because 31 of the 60 units tested failed to meet the manufacturer's specified limits of capacitance, dissipation factor, and dc leakage.
2) It was found that moisture resistance test followed by temperature cycling has a very deleterious effect on those capacitors which are not hermetically sealed, i.e., slug and foil tantalum capacitors, particularly those capacitors rated at 125°C.
   The physical appearance of the capacitors which were affected by high humidity exposure can best be described as:
   a) Cracked and bulging end seals caused by the internal pressures and temperature cycling (See Figs. 1-3).
   b) A slight leakage of electrolyte at both the seal periphery and the lead exit (See Figs. 4-6).
   c) "Pinhole" types of ruptures indicated by greatly increased dc leakage (See Fig. 7).

   It is interesting to note that, with the exception of the condition noted by increased dc leakage, there was not a great change in measured electrical parameters as a result of these factors after 1000 hours additional testing.
3) Storage at maximum rated temperature is very detrimental to foil and slug tantalum capacitors. A 15-20 per cent loss in capacitance can be expected in a 1000-hour period.

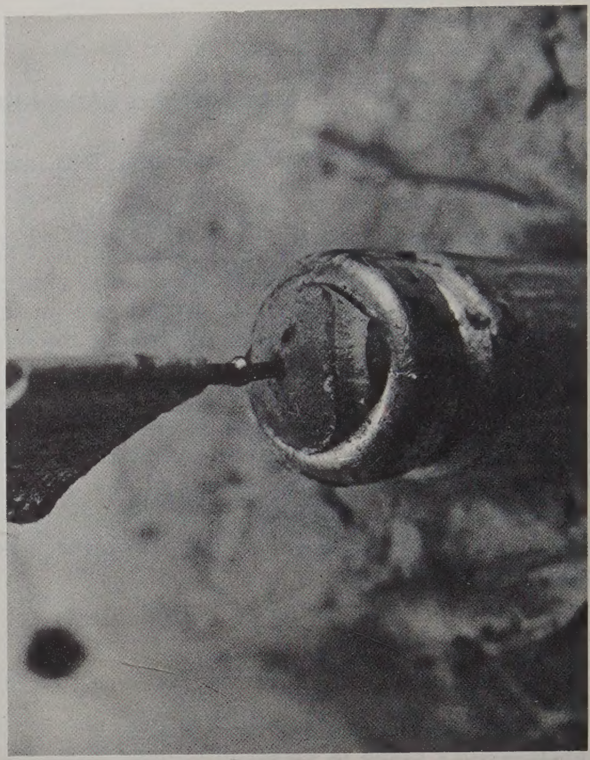

Fig. 1.—Wet Slug (coded orange #6) following step #6, temperature cycling. This unit has been subjected to steps 1-6. Note that in spite of the "popped" seal, there is no indication of electrolyte, nor was there any drastic change in measured electrical parameters.

4) Simulated altitudes in excess of 200,000 feet seem to affect the non-hermetically sealed units in much the same manner as moisture resistance followed by temperature cycling, as previously mentioned.

When these tests are completed, results will be immediately available through the Interservice Data Exchange Program (IDEP).

Potentiometers: There has been a recent attempt to eliminate the need for trimming potentiometers in satellite electronic systems through close circuit design and application of high reliability parts with suitable derating to minimize any operating point drift. As desirable an effort as this is, it seems at the present time to be practicable only for relatively simple systems. The state of the art in many component areas has not progressed to the point of drift free operation, particularly in the semiconductor area. Consequently, in highly complex systems, the elimination of a device which will compensate for variation in operating characteristics is still

Fig. 2.—Foil (coded red #6) following step #6, temperature cycling. This unit has been subjected to steps 1-6. There was no drastic change in measured electrical parameters.

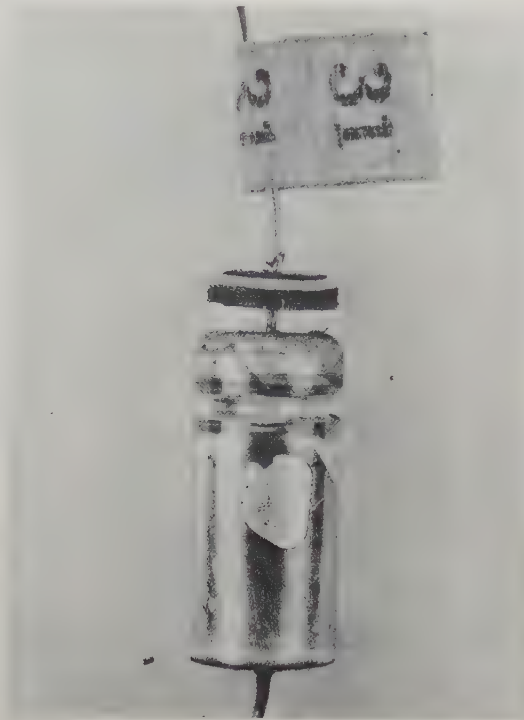

Fig. 3.—Wet Slug (coded orange #31). This condition was noted while monitoring the surge voltage test. At this time this unit had seen only one cycle of surge voltage. The only previous environmental history is temperature cycling. Capacitance has dropped to approximately 1/2 normal.

desirable. Another consideration which backs the need for a trimming device is that the design of the satellite equipment is not yet static. Continuous improvements are being made, and required equipment performance varies from vehicle to vehicle. Such a state of continual improvement does not permit circuit design of such close tolerances as to negate the need for potentiometers.

Since potentiometers must be utilized, it is important that their function and use be analyzed. In essence, as the trimmer potentiometer is now used in LMSD design, it is required to perform its operation in two separate and distinct ways. While the satellite rests on the ground, the potentiometer performs service as a variable resistor, used for adjusting and balancing circuits. But once in flight, the unit is required to operate as a fixed resistor. It will never be cycled again. Such demands obviously necessitate a hybrid unit which must meet a double modus operandi. Rigid demands must be met to fulfill this condition. A unit is required which possesses the sensitivity for incorporation into delicate circuits for balancing purposes, and yet is rugged enough to stand long lifetime operation with little or no change in value.

Extensive accumulation of test and life data reflects a basic instability of design, for all units tested or investigated reveal low humidity resistance and limited life. The causes for potentiometer shortcomings are inherent in their design. The exit of multiple leads from the case and the piercing of a lead screw through the case make adequate sealing extremely difficult. Short lifetimes result from the use of resistance wire in the range of one-half mil for achieving high resistance values in small cases. Composition units do not possess this weakness, but they are hindered by low-power dissipation and instability. It can be seen that, although trimmer potentiometers are a necessity in R & D programs, present designs leave much to be desired in performance and construction (See Fig. 8).

To insure reliable part operation for 10,000 hours unfortunately requires test periods of many times that duration. LMSD's test program on potentiometers [2] follows the same design as the capacitor tests. Environmental tests will be run in a flight sequential manner. Each and every test unit will be subjected to all environments, followed by a 10,000-hour life test. It is felt that such a

Fig. 4.—Capacitors Orange #34 and #37 (top to bottom), after 322 hours of temperature cycling life testing.

Fig. 5.—Capacitor Orange #21, after 322 hours of temperature cycling life testing.

procedure will provide a more realistic evaluation of a part's ability to withstand those conditions which it will meet in orbit. Following the conclusion of these tests, LMSD intends to work with the manufacturers toward the development of potentiometers which possess the characteristics of low noise, high resolution, low wear, reasonable stability, and high heat dissipation. It is the present feeling that materials must be developed to provide better performance from these parameters. Also the problem of case sealing will always exist, permitting the ingress of moisture and contaminants. Until the day of high reliability and stability is achieved that will permit potentiometer-free circuits, LMSD will continue their use, and continue its evaluation programs to assure that the best of the market is utilized.

Magnetic Latch Relays: Although nonlatch relays are employed in the satellites, with test programs being conducted on a few units, the major interest lies in microminiature magnetic latch designs. A most important consideration for long-life satellite is power consumption. The ability of programmed pulses to transfer relay contacts to either latch position without further power drain means the saving of valuable energy from the storage batteries. Another incidental advantage was realized in the vehicle check-out area. In some phases of vehicle testing, problems arose because of the presence of coil voltage which was necessary to check circuits containing normally open contacts. Magnetic latch units permitted the checks of circuits containing normally open contacts to be made with unenergized coils.

A comparison test [3] of several manufacturers' microminiature units is presently out for bid. The experiment was designed to provide step stresses to levels in excess of rating to reveal failure modes. Units surviving a sequence of environments (and it is hoped that a few will survive) will be life tested, under different loads, until failure occurs. One failure criterion for these tests is a contact resistance exceeding 0.05 ohms. Again, no attempt will be made now to delineate the minute details of the test design, but copies of the test specification are available upon request. [3]

Thermostats: A major problem in long-life satellites is the temperature control of certain components. Temperature cycling, which is widely varient and depends upon such factors as spin rate, altitude, dimensions, time of year, etc., is forecast between -65°C and +82°C for one series of

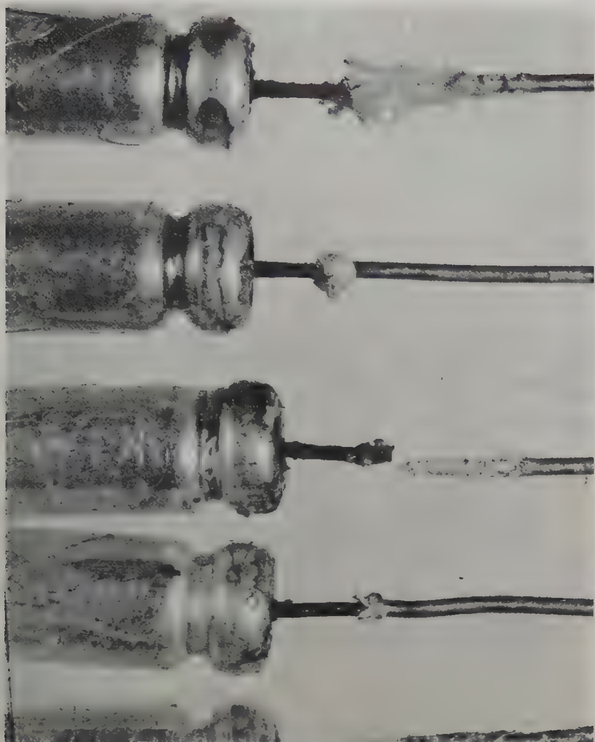

Fig. 6.—Capacitors Black #52, #50, #49, #46 (from top to bottom), after 322 hours of temperature cycling life testing.

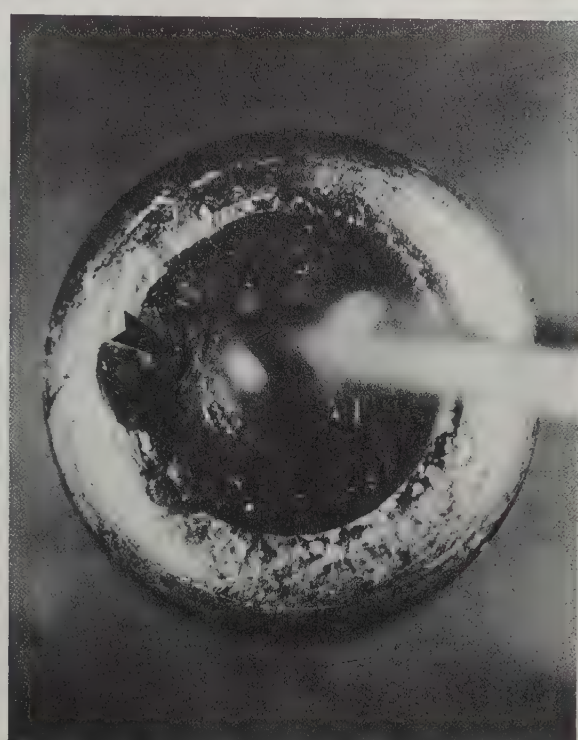

Fig. 7.—Wet Slug (coded yellow #27) following step 5, moisture resistance. Arrow points to rupture in seal. This unit had not been subjected to any prior environmental tests. Subsequent parameter measurements revealed an increase in leakage current by a factor of 100.

satellites. A critical application in one component required a ± 1°F tolerance. A study of available thermostats, mostly bimetallic types, which would meet the size and weight requirements resulted in failure. In an attempt to stimulate interest LMSD drew up a list of requirements to discuss with thermostat manufacturers. The list of the major items of the specification are indicated in the Appendix. Of the listed performance requirements the most difficult to meet was the fail safe feature. The normal mode of failure of the power transistor was a short which would cause continuous heating.

Another alternate method of temperature control was found to be a mercury column thermostat working into a relay. This type has been successfully used in ballistic missiles. Extensive evaluations are presently under way on these units by an LMSD subcontractor, and the results of the testing to date have been satisfactory. The selection of a second source for these units is a current problem. Similar units tested have experienced mercury separation and one vendor's unit shipped by commercial aircraft shattered. (This proved to be the cheapest and shortest environmental test performed by Lockheed to date.)

For applications that can tolerate wider temperature extremes, ± 5°F, one vendor has supplied a disc type unit which has performed over 200,000 unit-cycles to date without failure under rated load. Other methods of temperature control have been evaluated including mag-amp devices, but these were usually discarded because of size, weight, or efficiency.

The previously mentioned tests represent only a small part of the total testing being performed by LMSD and its associates and subcontractors. Data from these tests are received continually and are available through the data exchange system.

PROCUREMENT SPECIFICATIONS

The urgent need for high reliability specifications was adequately expressed in the recent report by the Ad Hoc Study Group on Parts Specification Management for Reliability. [4] This report, released in May, 1961, included the following recommendations:

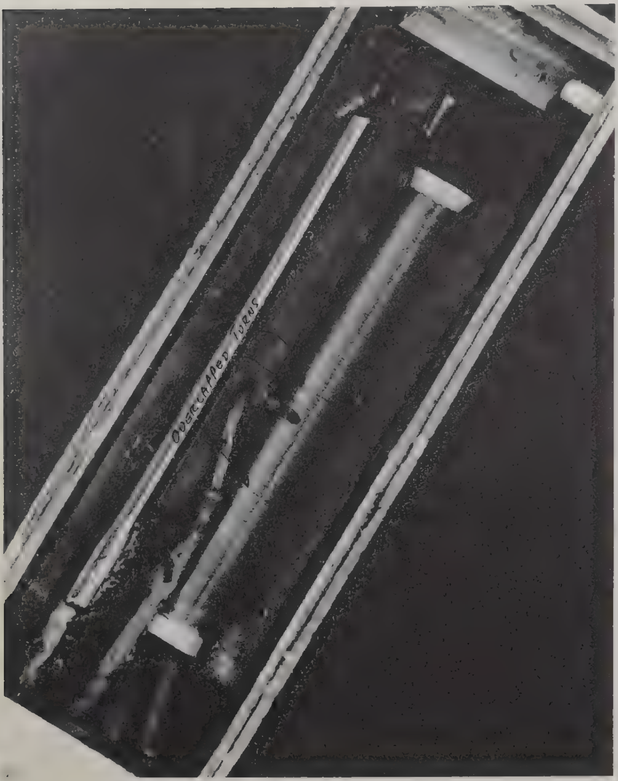

Fig. 8.

1) Reliability requirements should be incorporated in the specification including the test requirements necessary to assure the attainment of reliability levels defined therein.
2) The procedure for qualification approval should be revised to establish qualification for a specific reliability level. Qualification approval should be re-evaluated periodically to determine continuing compliance with the specification requirements.
3) The parts manufacturers should be responsible for all acceptance testing called for by the specification. However, the final responsibility for acceptance or rejection of parts should remain with the procuring agency.
4) Effective administrative control should be established to insure maximum use of standard parts.
5) Finally, emphasis should be placed on the collection and dissemination of technical data on electronic parts. A central organization should be established for this purpose.

The last recommendation has been covered earlier in this paper and additional comments are not necessary. The first four recommendations are centered on a new version of specification. After a detailed study of these PSMR reports, LMSD initiated the preparation of a series of specifications which would incorporate the above recommendations.

The first of these, to be used as a trial run, was on fixed film resistors. [5] Preliminary copies have been completed and sent to several resistor manufacturers for comment. In the near future LMSD expects to negotiate the purchase of resistors which will meet this specification. The principal features of this specification can be summarized as follows:

1) Final reliability requirements are specified at a 90 per cent confidence level in decade values at failure rates from 1.0 per cent per 1000 hours to 0.001 per cent per 1000 hours.
2) The marking on the individual resistors must contain a failure rate designation and a date code to indicate the manufacturing lot identity.
3) Tolerances are generally in accordance with MIL-R-10509D. However, if it is determined through the test program that the part is capable of meeting more stringent tolerances, they will be modified. Life tests have been extended to a minimum of 2000 hours, with some units being tested to 10,000 hours for failure rate certification and stability verification.
4) The manufacturer is required to have parts qualified at an approved test facility (which may be his own) and submit these data for qualification approval. The manufacturer is further responsible for lot sample testing and must submit these data with each lot for periodic re-evaluation.
5) Statistical screening techniques have been included to eliminate units within a given lot which exhibit anomalous behavior.

Prior to the PSMR study, LMSD had issued noteworthy specifications. In addition to severe design, performance, and environmental requirements, the specification embodies stringent Reliability and Quality Assurance provisions. A specification for double diffused silicon NPN transistor [6] specified a mean-time-to-failure of 10^7 hours while dissipating 5 mw in an ambient temperature of 70°C. Reliability documentation describing the methods for demonstrating these mean-times-to-failure were requested as a part of the quotation. This specification also requested a description of the process controls, design consideration, and life test procedures for these units.

As a part of the acceptance tests, regular life tests for 1000 hours were performed on samples from each lot. Acceptance inspection required 100 per cent processing for ageing, temperature cycling, seal test and shock and tumble tests. Semiconductor manufacturers have supplied parts to these specifications, thus indicating the willingness of industry to work toward higher reliability.

APPLICATION CRITERIA

Once a superior part is identified and its manufacturing processes controlled, the design engineer must have data readily available so that he can allow for the part instabilities. Hence a major point of the parts program is to identify for the engineer the drift of critical parameters in each application and to facilitate his selection of values and part types compatible with his design requirements.

In long-life applications, size and weight are trade-off factors for failure rates. Whether an engineer selects a 1/4-watt resistor for a 1/8-watt application instead of a 1/2-watt item with its lower failure rate is influenced—but not dictated—by factors other than reliability. Reliability factors here do include such stresses as thermal and cosmic radiation effects in addition to the conventional stresses of launch shock, vibration and acceleration, and orbital high vacuum. The major unknown degradation factors include temperature cycling, prolonged low ambient pressure, and proton radiation. Temperature cycling through a 40°C excursion within the range of -65°C to +85°C may be expected during each orbit. Several thousand thermal cycles can occur during a mission dependent upon the satellite attitude rate and altitude. Some fatigue failures could be expected in diodes, magnetic core matrices, film resistors, transistors and relays unless the piece parts are adequately evaluated prior to use. Degradation caused by temperature cycling alone has not been documented on all part types yet, but experimentation will continue on this factor in our program.

Radiation in the outer and inner Van Allen belts will cause degradation when high energy protons impinge on electronic materials such as semiconductors and dielectrics. The extent of instabilities is scheduled for laboratory and flight investigations, and the resulting degradations are established as design criteria.

Prolonged performance in low pressure environments will accentuate parametric drift through outgassing, evaporation, sublimation and redeposition. Any electronic part which is not hermetically sealed is suspect. Even those that apparently have seal integrity will develop a few "leakers" in a complex satellite unless the technique is well proven. At ground ambient, non-sealed units or "leakers" can be contaminated with water vapor and other impurities which cause instability at an increasing drift rate on orbit. Redeposition on cold surfaces is a potential degradation factor, since electrical leakage can increase. Any exposed surface such as that on open connectors, slip-rings, relay or switch contacts, printed circuit boards, and antennas is susceptible to the deposition of inorganic and organic solids that will be present within the satellite. As soon as an application guide for this degradation factor is completed, it will be made available to all design engineers.

In addition to the surface temperature cycling noted above, the self-induced thermal stress may cause excessive drift. In order to conserve power from the batteries most equipment will be energized and de-energized to accomplish the minimum flight objectives. Adequate design criteria to conduct heat away from parts must also be disseminated. Another aspect of the equipment duty cycle will be induced voltage transients on many parts. This stress generally can be controlled; however, when it is not minimized, serious degradation can occur.

Design criteria covering the modes of failure are of prime importance when selecting elemental redundancy. If the failures are practically all of the "open" type mode, a redundant series element is of no value and a parallel technique should be given greater emphasis.

CONCLUSION

The future of the space programs of this country depends to a greater degree upon the stability of the basis piece parts. Complex equipment employing thousands of parts which are expected to operate long periods without maintenance require these parts to be of "super" quality. The four point plan presented in this paper is: 1) the utilization of an effective interchange of information complemented with 2) a vigorous evaluation and development program followed by the 3) preparation of high reliability specifications and 4) the dissemination of design criteria. This plan outlines, in a cursory fashion, the major facets for achieving the objectives of the piece part program in which Satellite Systems is presently engaged.

APPENDIX

Temperature Controller

Control Sensitivity: Each unit shall control within $\pm 1°F$ around the control point.

Power Control: The output shall be capable of conducting at least 2 amperes continuously and withstand a forward voltage of 35 volts when non-conducting.

Power Loss: A design goal of less than 1/4 watt shall be used.

Sensor: Shall include a miniature (thermistor) sensor located remotely from the electronic package at any selected distance up to 5 feet from the package.

Operating Ambient Temperature: During use, the electronic package will be mounted on a structure which is maintained at $70° \pm 6°F$.

Electronic Package: The thermostat shall be a transistorized electronic package with a power transistor controlling the current to the load.

Fail Safe: Complete system shall be designed for fail safe operation.

Size: A design goal of 2 cubic inches or less shall be used.

Shock and Vibration Environment: These units are for satellite use and shall be capable of operating during a 50-g, 11-mg shock and 3-3000-cps, 20-g (max. 1/2 inch d.a.) vibration environment.

Other Environments: Must meet other environments as specified in LMSD environmental specification LMSD 6117B.

Reliability: Reliability is of prime importance, and the design and all parts used shall be chosen with this major consideration.

REFERENCES

[1] Reliability Test Procedure, "Fixed Electrolytic Capacitor (Tantalum)," February 19, 1960.

[2] Reliability Test Procedure, "Variable and Wirewound Miniature Variable Resistor," November 15, 1960.

[3] Reliability Test Procedure, "Microminiature Latching Relay," September 25, 1960.

[4] OASD, "Ad Hoc Study Group on Parts Specification Management for Reliability," (PSMR-1), May, 1960.

[5] LMSD Specification "Fixed Film High Reliability Resistor," October, 1960.

[6] LMSD Design Control Specification, "Double Diffused Silicon NPN Transistor," May 5, 1960.

Design by Worst-Case Analysis: A Systematic Method to Approach Specified Reliability Requirements

W. D. ASHCRAFT,† member, IRE, and W. HOCHWALD,† senior member, IRE

Summary—Design criteria which result in a systematic method to approach specified reliability requirements of equipment are essential to the development of complex electronic systems. A practical approach to designing equipment which lends itself to theoretically valid reliability prediction has long been sought. The worst-case analysis offers an answer in terms of a simple, well-organized, analytical method. Furthermore, application of this method results in a number of factors which benefit the component design engineer, the system design engineer, the administration of the engineering organization which applies these techniques, and the manufacturer of the component parts. The subject of worst-case criteria will be introduced, and the resulting effects on hardware and the engineer will be examined. The procedure for performing the worst-case analysis will then be described, and sample circuits designed in this manner will be shown. Lastly, the relation of worst-case criteria to statistical theory will be described, and the validity of worst-case criteria for reliability prediction will be shown.

I. INTRODUCTION OF WORST-CASE CRITERIA

The concept of worst-case criteria for component (defined as an assembly of individual parts) designs is not new. The worst-case criteria can be stated as follows:

1) A component must perform its function by exhibiting each and every specified parameter within tolerance when all of its part parameters (as well as signal, power, and environmental input parameters) are at their worst-case values. The worst-case values are defined as those values which are not mutually exclusive and lie within the tolerance limits, but tend to affect an operating parameter of the component in the most adverse possible manner.[1]
2) No part shall be subjected to stresses greater than those specified for the part under any conditions of ideal or nonideal conditions of component operation.

The facts that are generally not recognized about worst-case criteria are that these criteria 1) enable rapid evaluation of quality of performance of a circuit configuration, 2) are rarely too severe in terms of "realistic" stresses, 3) do not result in overly-complicated devices, and 4) are necessary and sufficient to predict minimum component reliability when statistically valid parts reliability data are available. Once these items are recognized and the worst-case analysis is applied (possibly on an initial trial basis), a number of additional significant benefits become apparent in terms of resulting influences on the component design engineer, the system design engineer, the engineering organization, and the manufacturer of component parts.

Returning to the facts generally not recognized about worst-case criteria, item 1), the ability to evaluate rapidly the quality of performance of a circuit configuration, represents an exceptionally valuable tool for initial circuit development and part value optimization. Since worst-case considers tolerance endpoint values only, the calculations to determine component performance limits are generally simple. The need for extensive component testing is often eliminated because parameter variations have been taken into account in the initial worst-case design. Thus, fewer but more carefully planned component tests are required to confirm worst-case analysis results. This generally reduces over-all development costs and reduces the time period required for completion of development and testing.

Item 2), the severity of worst-case criteria in terms of realistic stresses, is most frequently questioned. It is difficult to provide a conclusive, rigorous answer to this question. However, in an heuristic sense, a number of practical examples indicate that worst-case is approached under many

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[1] In borderline situations, these worst-case values can be adjusted (narrowed) by taking into account the specified allowable failure rate from tolerance build-up and the effect of the critical parameters in question on the desired output function. This is further explained in Section IV of this article and in Appendix A.

readily conceivable situations due to correlation between critical parameters in a given component. One example is a linear transistor amplifier composed of several gain stages operated from a common power supply whose output is at the lower extreme of its tolerance. In this case, the gain of each stage is normally voltage sensitive; hence, all amplifier stages will simultaneously exhibit low gain. If the amplifier were operated at low temperatures, the Betas of the transistor gain stages would also simultaneously approach the lower limit, and again the worst-case situation is approached. It can be shown that correlation of this type exists in a sufficient number of critical parameters so that realistic behavior can be expected to approach worst-case conditions to a very close degree, particularly at the extremes of the specified operating region.

Further justification of design to worst-case criteria lies in the area of safety factors which are rarely applied in electronic design. Use of worst-case criteria automatically incorporates reasonable safety factors without overdesign.

Item 3), the question as to whether or not design to worst-case criteria results in overcomplicated circuits, can only be answered by empirical results. Twenty circuit configurations were examined. These contained 6 to 18 transistors and their associated circuit components. The circuits were chosen at random and presumably designed by means of nominal analysis, breadboarding, and subsequent testing. Circuits which were capable of performing their functions under nominal conditions could readily be modified to pass worst-case criteria by relatively minor circuit changes or component parts changes. In some cases, it was possible to remove superfluous parts. Circuits which exhibited failure tendency because of overstressed parts sometimes required addition of component parts to limit the exceeded voltage, current, or power rating.

Perhaps the final and strongest point in favor of worst-case criteria is item 4), which states that worst-case criteria represent the necessary and sufficient conditions for prediction of minimum component reliability. This will be discussed in considerable detail in the final portion of this paper.

II. EFFECTS OF WORST-CASE CRITERIA ON HARDWARE AND THE ENGINEER

A startling result of applying worst-case analysis criteria lies in the number of side benefits that are derived by the component design engineer, system engineer, the administration of the engineering organization, and the manufacturer of the component parts. As far as the component design engineers are concerned, the worst-case criteria establish a minimum acceptable standard for component design which is clearly defined and possible to adhere to. Use of poorly analyzed circuits, untried or unspecified devices, and inadequately understood designs is automatically eliminated since worst-case criteria cannot be properly established in those cases. Worst-case analysis calculations are relatively simple, because by nature end-point calculations do not involve statistical or nonlinear theory. Programs for digital computers are readily developed for worst-case solutions and result in efficient calculation of the various worst-case possibilities by successive insertion of the appropriate parameter tolerance limits. The system design engineer benefits in terms of receiving more accurate data on individual component performance. This facilitates system design decisions involving necessary trade-offs and compromises. Over-all system accuracy and performance can be predicted more accurately when worst-case behavior of individual components is known.

Administration of an engineering organization which applies worst-case analysis is aided by the fact that uniformity of design is less dependent on the individual engineer's capability; engineers can be trained more effectively; and engineers with a relatively small amount of experience can be utilized to analyze portions of components. Furthermore, a worst-case analysis results in an accurate record of detailed design considerations. The abilities of engineers performing analyses can be evaluated better by supervision. Engineers who have performed designs by worst-case criteria can usually provide more accurate cost estimates for development of new components and also for maintenance costs; hence, manpower loading and maintenance costs can be predicted more accurately. Uniform control of engineering methods and procedures is a strong by-product of applying worst-case analysis. Usually, this leads to the acceptance of standard component designs.

Finally, the beneficial effect of worst-case analysis on the manufacturer manifests itself in the fact that he can depend on more careful consideration of application specifications on the part of the development engineer. It is true that the engineer will also request considerably more component parameter data from the vendor; however, cost of performance and degradation tests to supply these data is greatly offset by the assurance that the

vendor's part will be properly applied and thus, in general, will live up to the reliability predicted by the vendor.

It is possible to extend the discussion of effects of worst-case analysis by considering functions of additional agencies that participate in product design or manufacturing. For instance, quality control engineering is benefited by receiving worst-case component parameter limits, since this enables the establishment of more meaningful and optimized specifications and manufacturing checks. System checkout and analysis of system behavior are simplified when component performance extremes are known. Similar considerations extend to virtually all agencies that participate in product design or manufacturing.

III. PROCEDURE FOR WORST-CASE ANALYSIS

The worst-case analysis is an analytical tool intended to aid the engineer in the achievement of component designs that satisfy worst-case criteria. The worst-case analysis requires:

1) Complete determination in detail and with tolerances of all the basic functions that the circuit is required to perform.
2) Determination of all conditions (primarily tolerances, damaging stresses, noise, and handling) which tend to prohibit the circuit from performing each function as required.
3) Proof that the circuit will perform each function as required, even though all failure-causing tendencies occur simultaneously at their maximum values (unless some are mutually exclusive; in this case each set of failure-causing tendencies is considered separately).

The effectiveness of the analysis is dependent on the accuracy, completeness, and reasonableness with which the engineer or group of engineers specifies the functions and determines the failure-causing tendencies.

The basic circuit functions to be determined in stage 1 must include all possible circuit states. A circuit state is defined as one set of voltage and current conditions in a circuit for which only one set of matrix equations, loop equations, node equations, simultaneous equations, or signal flow graphs can be written. This set of equations or graphs will apply only for this one state. Thus, for a typical circuit to remain in one particular state, all reversed biased diodes must remain reverse biased; all relays and mechanical switches must remain in their required ON or OFF state; all saturated transistors must remain in saturation, etc. If one or more circuit elements change so that a different set of equations or graphs then apply, the circuit is said to have changed states. This changing of states is called a transition point.

In general, a circuit is required at certain times to be in particular states. For each state there is required a specified input-output function. If at a certain time the circuit is in the wrong state, the specified input-output function usually will not be met. Thus, all states that a circuit is required to exhibit must be listed. Moreover, for each state a selection must be made of the values of circuit parameters, input signal conditions, power supply voltages, etc, within tolerance which will tend most strongly to cause the required state to disappear. In addition, it must be proved that even with these values, the circuit will remain in the required state.

After it is proved that each required state will be exhibited at the proper times, the circuit's requirements for each state must be listed; and for each requirement a selection must be made of the values of circuit parameters, input signal conditions, power supply voltages, etc, within tolerance which will tend most strongly to cause the requirement to fail. Then it must be proved that even with these values, the requirements will be met.

Each calculation must be made with all part, circuit, and environmental parameters at one extreme of their tolerance limits. Whether the high or low extreme is selected will be determined as follows: If a maximum value is required, each parameter is selected at its extreme, which will maximize the value being calculated; similarly for the minimum. The type of calculation is called a worst-case calculation. The only exceptions to this rule are in the cases of higher-order effects and as power dissipation in an active element. In these cases all parameters and conditions are selected at their values within tolerance, which will maximize a maximum value calculation or minimize a minimum value calculation. In all calculations, especially in borderline cases, care must be taken to establish accurate equivalent circuits that yield useful results. Verification by means of controlled tests is occasionally required.

In cases where use of worst-case values is felt to be the direct cause of an undesirable increase in power dissipation, circuit complexity, or physical size, adjustment (narrowing) of worst-case values should be considered. This technique is explained in Section IV of this article and in Appendix A.

It is often simpler for analysis to break a component into several subcomponents, each with its own particular requirements. For example, a

superhet receiver can be divided into RF section, converter, IF section, second detector, audio, and power supply. Each of these subcomponents can be analyzed separately by determining its input-output requirements and equivalent circuits.

The analysis is a detailed consideration of each of the following steps:

1) Examination of component specifications for reasonableness and completeness.
2) Examination of functional test specifications for accuracy in realistic operating conditions and completeness in requiring measurement of all pertinent parameters.
3) Determination of tolerances of all applicable part and environmental input parameters after aging and use, and determination of the stress ratings for all parts.
4) Definition of all circuit states, and determination of the state of each part during each circuit state.
5) Determination as to whether or not each part will be in its required state and determination of all active element dc operating points for each circuit state under worst-case conditions.
6) Determination of all functional parameters, their values, and their tolerances. Examples of functional parameters are: gain; phase shift; phase margin; stability with feedback; loop gain during a transition state; frequency; load impedance; input impedance; output impedance, voltage, current, power; rise time, waveform; dc offset; balance; noise generated within one or more parts; regulation; stability of all adjustments that depend on tolerance, temperature, environment, aging, etc.; detection level for a threshold detector; timing; special logic; protective circuitry parameters.
7) Determination as to whether or not each functional parameter will be within its required tolerance under worst-case conditions.
8) Determination of the effects caused by system noises external to the circuit and coupled into the various input lines.
9) Computation of the maximum possible stress on each part for all normal or abnormal operating conditions. Examples of abnormal operating conditions are: abnormal signal condition; open or shorted load; reactive load feedback; turn-on and turn-off transient; plug-in; power supply overvoltage.
10) Examination of the designed component for susceptibility to pickup noise and interference coupling. Investigation of parts which have been mounted poorly to discover: whether these parts dissipate heat; are isolated from heat-generating parts; are capable of withstanding vibration, handling, and other environmental conditions.

An example of a circuit designed to meet worst-case criteria is described in Appendix B.

IV. RELATION OF WORST-CASE CRITERIA TO STATISTICAL THEORY

The worst-case criteria are stated in the introductory portion and are repeated here for the sake of continuity:

1) A component must perform its function by exhibiting each and every specified parameter within tolerance when all of its part parameters as well as signal, power, and environmental input parameters are at their worst-case values. The worst-case values are defined as those values which are not mutually exclusive and lie within the tolerance limits, but tend to affect an operating parameter of the component in the most adverse possible manner.
2) No part shall be subjected to stresses greater than those specified for the part under any conditions of ideal or nonideal conditions of component operation.

In order to fully understand the basis of these criteria, the following concepts are necessary: A component's operating characteristics are defined by certain basic parameters necessary and sufficient for proper system operation. These basic parameters are called "component parameters." The values of all part and input parameters of a component will be ultimately reflected in the determination of all the component parameters as either a continuous function or a discontinuous function. The value and tolerance of each component parameter are determined uniquely by the values and tolerances of the component's part and input parameters.

In general, each part parameter and each signal, power, and environmental input parameter of a given component has a statistical distribution at any instant. Limits may be fixed around the statistical distribution to define the tolerance of the parameter. An "intrinsic failure" is defined as the condition that one or more parameter values lie outside of the tolerance limits. Because all parameters can be described by statistical distributions, the probability of an intrinsic failure decreases with an increase in tolerance range. In

general, the lower the probability of component failure is required to be, the wider must be the tolerance range of each part and input parameter over which the component must function properly. The defined tolerance range of each part and input parameter can be derived from the required probability of component failure; the dependence of the component's failure on the value of that part parameter; and the statistical distribution of that part parameter over the operating life of the component. Thus, once the limits have been drawn on each part and input parameter, the component must operate within specification with any and all possible combinations of part and input parameters within their specified limits; otherwise, the probability of component failure will be greater than that specified.

A refinement for setting the limits on part and input parameters is offered by a method of worst-case value tolerance narrowing. This method retains the simplification of a worst-case-type analysis, but introduces maximum narrowing of parts tolerance ranges without causing the specified probability of component failure from tolerance buildup to be exceeded. The basic theory for this approach is given in Appendix A.

If each and every component parameter is within specification (even with all part and input parameters at their worst-case values within their specified limits and in a direction to maximize or minimize any component parameter), then each and every component parameter will be within specification with any and all possible combinations of part and input parameters within their specified limits. The worst-case criterion 1) must be met; therefore, if it is not, the component's probability of failure will be greater than that specified.

In general, the statistical distribution of each part parameter is dependent on the past history of the stresses to which the part has been subjected, especially if the fatigue or breaking stress is approached.

The statistical distributions of a part's parameters are conventionally determined by subjecting a quantity of parts to known stresses for known periods of time, and measuring the part's parameters. Usually, the greater the stresses to which a part is subjected, the wider will be the statistical distribution of its parameters. Thus, once the statistical distributions of a part's parameters have been determined for a particular stress level, the part must never be subjected to stresses greater than those specified, or the component's probability of failure will be greater than that specified. Therefore, the worst-case criterion 2) must be met, or the component's probability of failure will be greater than that specified.

V. RELIABILITY PREDICTION

Worst-case criteria 1) and 2) being justified, the ability to predict component reliability will be discussed. If there are available a) functions describing the component parameters as functions of all part and input parameters, b) the required limits on all component parameters, and c) the statistical distributions of all part and input parameters, these three items can then be combined by means of multiple integrals to yield an accurate value for the probability of component failure. (The number of integrals equals the number of specified component parameters. The order of each integral equals the number of independent parameters making up the component parameter under consideration.) However, usually one or more of the required items is not available.

A simplifying alternative to the preceding probability computation is available. If the component meets the worst-case criteria, and if the probability of intrinsic failure, as defined previously, is known for all parts, the probability of intrinsic failure for each part over the component operating life can be converted to an intrinsic failure rate. The failure rates of all parts can then be added to yield a failure rate which is greater than or equal to the actual component failure rate. (The "greater than" is included because in most cases, a part or input parameter can be slightly outside its specified tolerance without causing a component failure.) It is of interest that the tolerance narrowing alternative discussed in the previous section tends to minimize the differences between the predicted failure rate based on the sum of intrinsic failure rates and the actual failure rates which can be expected.

Notice that if the worst-case criteria are not met in full, the sum of the intrinsic failure rates of all parts will yield a failure rate which is less than, equal to, or greater than the actual component failure rate, and thus, is unbounded and useless as a predicted value for failure rate. (The "less than" is included because if the worst-case criteria are not met in full, there will either be combinations of part and input parameters within their specified tolerance which will cause component failure, or a part parameter will drift at an excessive rate due to excessive stress. This excessive drift rate will tend to cause premature component failure.)

Of special interest in applying the worst-case

criteria are borderline situations; e.g., a situation in which the engineer must determine whether the addition of one or more parts to limit the stresses on another part will increase or decrease the probability of over-all component failure. The correct decisions in these cases must be based on known effects of stresses on the statistical distribution of the part's parameters. These effects must be determined in a series of statistically valid tests for that part. Thus, once the valid statistical data are available to the engineer, he can make decisions and determine the effect of any such decision on probability of component failure.

APPENDIX A. DERIVATION OF METHOD FOR WORST-CASE VALUE TOLERANCE NARROWING

A certain parameter y, whose tolerance is being computed, is dependent on the values of n parameters, $X_1, X_2, \ldots X_n$. This relation is often given in the form of matrix equations. Associated with the X's are standard deviations, σ_1, $\sigma_2, \ldots \sigma_n$. These deviations occur because of a random parts selection process, not because of variances within a given part. The frequency distributions of the X's are not necessarily Gaussian. If all the X's are random and statistically independent, the standard deviation in y, σ_y, is given by

$$\sigma_y^2 = \sum_{i=1}^{n} \left(\frac{\partial y}{\partial X_i} \sigma_i \right)^2 . \tag{1}$$

Further study of (1) will reveal that if the $\frac{\partial y}{\partial X_i}$ are not constant, but dependent on the values of the X's, and if the rms values of the $\frac{\partial y}{\partial X_i}$ are substituted for the $\frac{\partial y}{\partial X_i}$, (1) will be exact. The rms values of the $\frac{\partial y}{\partial X_i}$ can be determined with a form similar to (1). The result is a long series of multiple cross-partial derivatives, each evaluated with all X's at nominal. Computation of these multiple cross-partial derivatives is prohibitive in length and complexity, even with a computer. However, if the magnitude of σ_i does not approach or exceed the magnitude of X_i (true for any practical electronic part), the error is negligible in assuming that $\frac{\partial y}{\partial X_i}$ (evaluated with all X's at nominal) is equal to the rms value of $\frac{\partial y}{\partial X_i}$. This assumption, therefore, is made.

The method given herein relies on the derivation of a parameter p which is defined so that

$$k \sigma_y = \left| \frac{\partial y}{\partial X_1} \right| pk \sigma_1 + \left| \frac{\partial y}{\partial X_2} \right| pk \sigma_2 + \ldots + \left| \frac{\partial y}{\partial X_n} \right| pk \sigma_n \tag{2}$$

holds where k is a constant to be determined and dependent on probability of tolerance failure. Thus, if $\overline{X_i} \pm pk \sigma_i$ are substituted for X_i in the matrix equations, the $\pm$ sign being chosen according to the sign of $\frac{\partial y}{\partial X_i}$, and the value of y computed, y will be equal to its upper or lower tolerance extreme, $\overline{y} \pm k \sigma_y$. If these tolerance extremes are within the required bounds determined from system requirements, the circuit is acceptable from a tolerance standpoint. The probability that y lies outside the required bounds then will be within required limits.

p, determined from (1) and (2), is given by

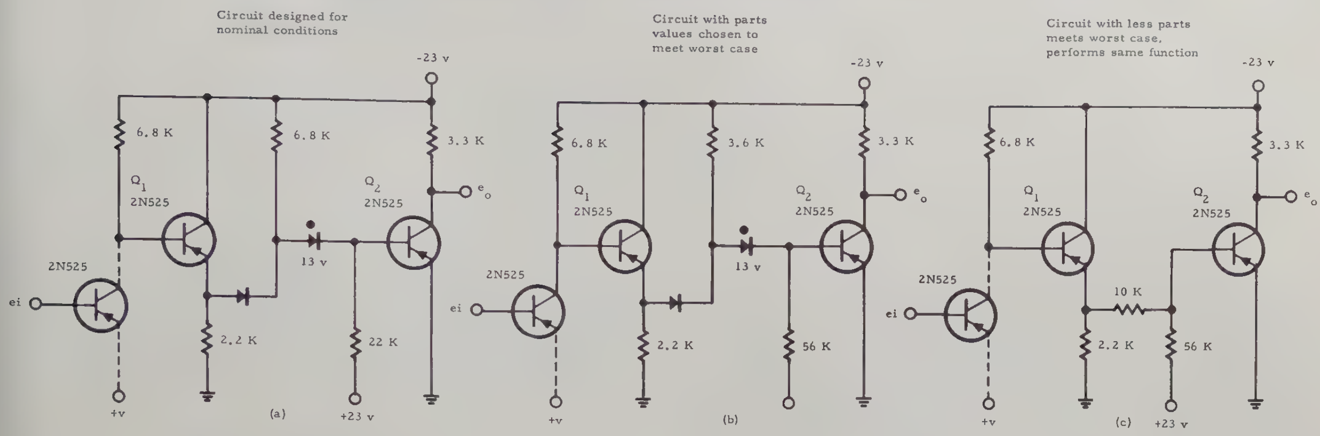
$$p = \frac{\sqrt{\sum_{i=1}^{n} \left(\frac{\partial y}{\partial X_i} \sigma_i \right)^2}}{\sum_{i=1}^{n} \left| \frac{\partial y}{\partial X_i} \right| \sigma_i} , \tag{3}$$

and is always in the range, $o < p \leq 1$. The partials, evaluated with all X_i at nominal, can be evaluated from the matrix equations. All σ_i can be determined either directly or indirectly from parts data. Therefore, a numerical value for p can be determined with (3).

k represents the allowed probability of failure from tolerance buildup on one end of one operational parameter. In (1), if the number of terms becomes large and the relative contribution of the largest term becomes small, the frequency distribution of y will approach a Gaussian distribution, regardless of the frequency distributions of the X_i. If the frequency distribution of y is Gaussian, the probability P_f that y will lie outside of one of its tolerance extremes, $y \pm k \sigma_y$ is obtained by integrating the Gaussian curve as follows:

$$P_f = \int_k^{\infty} \frac{1}{2\pi} e^{-x^2/2} \, dx . \tag{4}$$

Therefore, if the probability of failure P_f of one



Tolerance extremes of parts parameters

parameter	minimum	maximum
+23 v and -23 v ±1 percent power supplies	22.77	23.23
Resistors	-20 percent of value	+20 percent of value
13 v Zener diode	12 v	14 v
Diode forward voltage drop	0	1 v
Transistors are 2N525:		
h_{FE}	17	—
I_{co}	0	300 μA
V_{be}	0	1 v

Computed circuit parameters

parameter	Circuit (a) nominal case	Circuit (a) worst case	Circuit (b) worst case	Circuit (c) worst case
I_c of Q_2	6.96 ma	7.65 ma	7.65 ma	7.65 ma
I_b of Q_2	0.33 ma	* reverse 0.072 ma	0.66 ma	0.68 ma
required minimum h_{FE} of Q_2	21	—	11.6	11.2
maximum allowable I_{co}	1.1 ma	—	0.313 ma	0.313 ma

* Circuit fails to operate

Fig. 1.—Two-transistor saturated amplifier

parameter at one tolerance extreme is given, a value for k can be determined from (4).

APPENDIX B. EXAMPLE OF A CIRCUIT DESIGNED TO MEET WORST-CASE CRITERIA

The circuit chosen as an example is a two-transistor, saturated amplifier which is typically used to convert a sinusoidal input to a square-wave output. Fig. 1(a), (b), and (c) shows three versions of this circuit, as well as assumed parts variations and pertinent results of design calculations. The parts variations are typical for current military types when subjected to environmental stresses and prolonged periods of storage. Fig. 1(a) illustrates a design based entirely on nominal conditions which does not pass worst-case criteria. Fig. 1(b) illustrates the same circuit configuration with appropriately adjusted parts values to pass worst-case criteria. (It is to be noted that no parts were added.) Fig. 1(c) is a further version of this circuit which actually uses fewer parts and still passes worst-case criteria. Use of the circuit in Fig. 1(a) led to a number of failures due to marginal operation. The circuits in Fig. 1(b) and (c) eliminated this problem.

Correlation-Capability Studies

HOWARD L. BERKE,† member IRE

Summary—In missile production, a recurring problem is the measurement of derived parameters. Unlike volts, amperes, and ohms, these parameters do not lend themselves to standard black-box test equipment. Nevertheless, whatever test equipment is used for their measurement still must be closely correlated to yield consistent and reliable measures.

The Span Plan, which has been successful largely because it uses range estimates rather than actual variances, has shown itself to be the most practical method for conducting correlation studies on Sidewinder missile test stations.

After discussing the Span Plan in some detail, the author concludes that the Correlation Capability Program, in establishing and maintaining close correlation of test stations, has been a significant contributor to Sidewinder's success.

Controlling the quality of complex assemblies involves the measurement of many standard variables such as volts, amperes, and ohms. All of these can be checked by the use of relatively simple, universally standard meters; however, in missile production we are faced with the measurement of many variables which do not lend themselves to standard "black-box" test equipment. These variables are known as derived variables or derived parameters.

The problem is compounded because often not one, but three, four, or more test stations are individually affecting the derived parameters. A part which has passed one test station may fail at another or, even worse, could fail at a final test station at the customer's installation.

Since derived parameters cannot be checked by standard test equipment, it is essential to attain close agreement between test data for such parameters. In short, they should each be reading data at the same level despite the inherent variability in the test equipment, the test operator, or the missile. The term "capability" denotes the ability of the test equipment to measure some parameter closely enough to control the correlated characteristics. This is closely related to the precision of the equipment and indicates both errors in measurement and inherent variability. A capability study determines two things: first, if the test equipment is precise enough to measure a given parameter and second, if the test equipment is functioning properly.

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INITIAL INVESTIGATIONS

The desirability of setting up a correlation-capability program was obvious, and for some time such a program had been considered seriously. Sidewinder Quality Control Engineering had investigated several data evaluation techniques to find the method best suited to the Sidewinder Missile's particular requirements. It was found that for a correlation-capability study of only two test stations, the method of running sufficient paired-comparisons worked very well. The data from each station could be compared by use of the familiar "t" test, whose results show the inherent error, if any, of the testing process for the stations.

When three or more test stations are involved, the most efficient method is to use an analysis of variance for the correlation-capability study. This analysis can be planned so that variations resulting from test stations, test operators, and missiles can be isolated, but it is not possible to separate the inherent missile variance from the inherent test equipment variance.

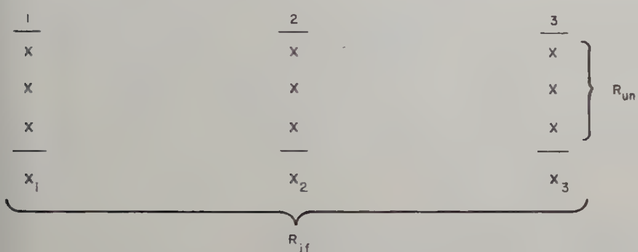
While the analysis of variance is an important data evaluation tool, it is impractical in production-line testing. To ensure valid results, great care must be taken to randomize those factors not to be controlled. A decision must also be made as to the amount of testing necessary to yield a test with good discrimination. Too few test runs will not detect important differences between test stations; too many test runs will tie up the production test equipment and wear out the missile or assembly used for the study. In addition, an analysis of variance can require a phenomenal number of computations, since at a given group of test stations as many as 30 "derived" variables must be evaluated. This problem can be surmounted, however, by using proper data processing techniques.

THE SPAN PLAN

Having found the classical analysis methods wanting from a practical, work-a-day aspect, it was decided to adopt the Span Plan method of capability analysis. [1]

In essence, the Span Plan retains the basic idea and most of the precision of the analysis of variance, but it is a more feasible method. It provides a neat, systematic, simple procedure for carrying out analysis of variance experimental designs by employing range estimates instead of actual variances. This is possible because the Span Plan procedure has been developed to the point where all computations and the number of tests required are predetermined by use of a standard Span Plan Worksheet. (See Fig. 1). It also employs the Pictogram for presenting the results of the analysis in a simple pictorial fashion.

Consider the following set of data:

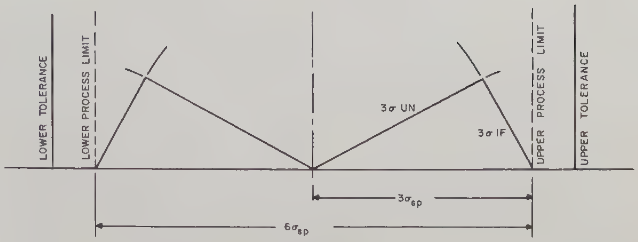


The variabilities to be measured are the "within-column" or "unresolved factor," the "column to column" or "isolated factor," and the "total variabilities" or the "total spans." These are abbreviated to "un," "if," and "sp," respectively.

Each reading is represented by an "X." The range (difference between maximum and minimum observation) of the observations within any column is denoted by R_{un}, and the range of the column sums by R_{if}. There are k columns and n readings in a column. By following a routine calculations, the ranges are converted to standard deviations and the total span ($\pm 3\sigma_{sp}$) is found to be

$$\pm 3\sigma_{sp} = \pm\sqrt{(3\sigma_{if})^2 + (3\sigma_{un})^2} \qquad (1)$$

The above relation may be represented graphically by the following "Pictogram."



The analysis proceeds from this point by answering mathematically the questions posed by the following six tests:

Test 1: Is the process meeting tolerances at this stage?
Test 2: Can the process meet tolerances at this stage?
Test 3: Does the isolated factor contribute 10 per cent or more to the total span?
Test 4: Can the process meet tolerances if the isolated factor is removed?
Test 5: Are the spans within columns different from one another?
Test 6: Does the total span at this stage differ from the unresolved span at the preceding stage?

APPLYING THE SPAN PLAN

For the specific problems met by Sidewinder Quality Control, little modification of the Span Plan routine was required. A correlation-capability study of a Sidewinder test station, of which, assume for this example, there are three individual test positions, begins with the Span Plan Worksheet (Fig. 1). Looking in the Table of Conversion Factors, tabulated on the worksheet, one finds under the number of test stations k = 3, that ten readings, n = 10, will have to be taken at each station. Therefore, 30 readings in all are required in order to get valid results. Care should be taken to ensure that the tests are sufficiently random to prevent time effects and extraneous factors from influencing results.

After the required number of tests have been performed, the Span Plan calculations are made. For the particular correlation-capability analysis used by Sidewinder Quality Control, it is not necessary to perform all Span Plan tests. Those which

S-PAN PLAN RECORD

DATA SAMPLE

STAGE

DATE	12/10/59
PART	Unit Test
OPERATION	voltage
TOLERANCES - UTL 90 LTL 70	
UNITS OF MEAS.	volts
SAMPLING PT.	
POSITION OF MEAS.	
ISOLATED FACTOR	position to position
UNRESOLVED FACTOR	within position

MEASUREMENTS

SAMPLE NO. AND IDENTIFICATION 1	2	3	4	5	6	7	8	9	10	TOTALS OF ROWS
84	82	85								251
83	83	85								251
83	83	84								250
84	84	84								252
84	84	84								252
82	84	85								251
84	83	84								251
83	84	85								252
81	84	85								250
84	84	84								252
TOTALS OF COLUMNS										2512
832	835	845								ΣX CHECK
RANGES WITHIN COLUMNS										
3	2	1								

		SUMMARY
ΣX 2512 /kn 30 =	→	$\bar{\bar{X}}$ 83.7
RANGE OF Run 2 =	→	PRun 2
ΣRun 6 /Cun 3.12 =	→	3σun 1.922
RANGE OF COLUMN TOTALS → Rif 13 /Cif 2.01 = 6.48		

COMPUTATIONS

TABLE OF CONVERSION FACTORS									
K	2	3	4	5	6	7	8	9	10
n	10	10	9	8	7	7	6	6	6
Cun	2.08	3.12	4.00	4.80	5.46	6.37	6.80	7.65	8.50
Cif	1.49	2.01	2.24	2.34	2.36	2.50	2.42	2.52	2.60
Q	.57	.78	.91	1.01	1.09	1.15	1.22	1.24	1.27

3σif	3σsp	
Rif / Cif = 6.48	$(3\sigma \text{if})^2$ = 3.82	
$(\text{Rif}/\text{Cif})^2$ = 41.9	$(3\sigma \text{un})^2$ = 3.7	σ_{sp} = 0.915
$(3\sigma \text{un})^2$ = 3.7	Sum Sq = 7.52	
Diff = 38.2	$\sqrt{S.S.}$ = 2.74 →	3σsp 2.74
$\sqrt{\text{Dif}}$ = 6.19	$\bar{\bar{X}}$ =	
$\sqrt{n}$ = 3.16	$\bar{\bar{X}} + 3\sigma_{sp}$ = →	UPL
∗ 3σif is 0 if NEG	$\bar{\bar{X}} - 3\sigma_{sp}$ = →	LPL
$\sqrt{\text{Diff}}/\sqrt{n}$ = 3σif	← →	3σif 1.954

	YES	NO
TEST NO. 1		
UTL = LTL =	not applicable	
UPL = LPL =		
TEST NO. 2		
UTL - LTL = 90 - 70 = 20		X
$n\sigma_{sp}$ = 2 ($3\sigma_{sp}$) = 2(2.74) = 5.48		
TEST NO. 3		
$3\sigma_{sp}$ = 2.74		
$3\sigma_{un}$ = 1.922		X
Diff = 0.818		
Diff / $3\sigma_{sp}$ = 0.298 or 29.8%		
TEST NO. 4		
UTL - LTL = 90 - 70 = 20	X	
$6\sigma_{un}$ = 2 (3σun) = 2(1.922) = 3.844		
TEST NO. 5		
Range of R un = PR un = 2		
Range of R un / 3σ un = 2/1.92 = 1.041		
Significance Value (Q) = 0.78	X	

PICTOGRAM (STAGE)

CONCLUSIONS:

CHECK AGAINST PRECEDING STAGE: (TEST NO. 6) not applicable

SP/UN = UPPER LIMIT / LOWER LIMIT

REMARKS: Position #3 appears to be insensitive and high

DECISION:

Fig. 1.

are pertinent to the Sidewinder are as follows:

Test 2: Shows how the positions as a group compare with respect to the tolerance range permitted.

Test 3: Indicates whether it is worthwhile to seek methods of reducing position-to-position differences.

Test 4: Supplies an indication of how good things would be if position-to-position differences could be eliminated.

Test 5: Checks whether the variability of each position is of the same magnitude as the other positions.

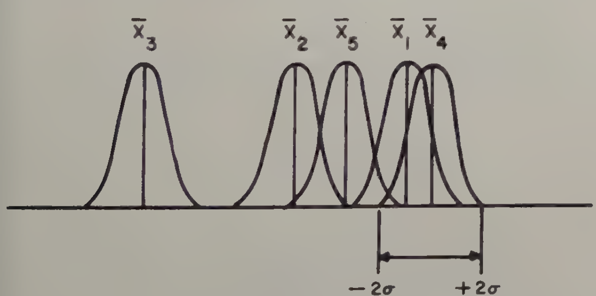
After the tests are performed, the results of the analysis are presented to management with recommendations for corrective action, if needed, or confirmation of the test stations' acceptable correlation and capability.

For this purpose, the span plan worksheet is not sent to management in its standard form. Instead, the key answers are abstracted from it and entered on a Correlation-Capability Summary Sheet (Fig. 2).

In conjunction with the summary sheet, a bell-shaped frequency curve is sketched about each individual test position's average value. This curve is used, instead of the Span Plan Pictogram, to portray visually how each test position reads a derived variable with respect to the other positions in the group. The following illustration shows a typical frequency curve for five test positions.

About each test position's average value, the 95 per cent confidence limits have been constructed. These $\pm$ two standard deviation confidence limits are obtained from the ASTM Manual on Quality Control of Materials.

Positions which are satisfactorily correlated in most instances should have some overlap of frequency distribution.



Even after corrective action, some variability in test processing will exist. This is particularly true of lower order assemblies where the precision of measurement usually is such that one reading of a given characteristic is not satisfactory to pass or reject the assembly.

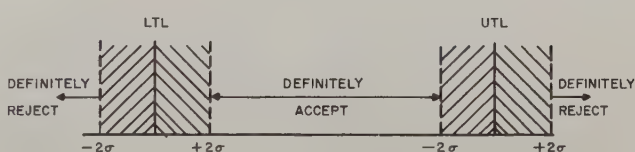
In such cases, it has been found desirable to construct a "gray zone" representing the area of indecision around each tolerance limit. This gray zone is established by adding and subtracting two standard deviations about the upper and lower limits. The "gray zone procedure" is as follows:

1) If the test equipment is not satisfactorily correlated, the proper standard deviation to use is σ_{sp}. This allows for the fact that there is no certainty regarding which of the positions is reading a true or absolute value.

2) If the test equipment is considered capable ($6\sigma_{sp}$ is less than 25 per cent of the allowable tolerance range) but there are reasons for believing the positions are not correlated, the gray zone boundary should be determined by a band of $\pm 2\sigma_{sp}$, about the UTL and LTL respectively.

3) If the equipment is satisfactorily correlated, the gray zone boundaries are established using $\pm 2\sigma_{un}$ limits about the boundary values, UTL and LTL.

4) If Test 5 of the Span Plan shows that the σ_{un} is not homogeneous for stations, the largest σ_{un} is used to establish the $\pm 2\sigma_{un}$ limits about boundary values. A typical gray zone configuration is shown below:



With this technique, if the first test reading falls in either of the gray zones, the technician makes a second independent test on the same test station. The average of the first and second tests is compared to the tolerance limit, and a decision is made either to accept or reject the assembly.

If the difference between the first and second readings is greater than $\sigma_{un}\, d_2\, D_4$ (the upper control limit for ranges of two independent tests where d_2 and D_4 depend upon the sample size n and may be read from Table 82, page 115, [2]), it is necessary to find out why. Possible causes for large discrepancies could be instrument or read-out error, equipment malfunction, or sudden severe changes in environmental conditions. Whether or not the cause can be determined, it is necessary to make a third test in order to reach a decision.

In addition to the gray zone technique, information from the correlation-capability analysis is

SIDEWINDER QUALITY CONTROL ENGINEERING

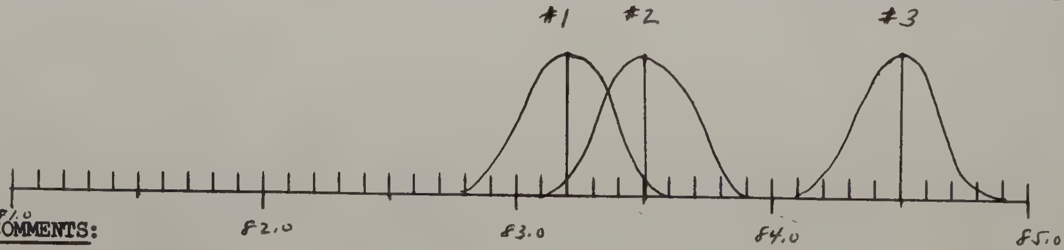
TEST STATION CORRELATION - CAPABILITY SUMMARY Sample

Test Station: Unit	Date: 12/10/59
Characteristic Measured: voltage	Sheet: 4 of: 6
Unit of Measurement: volts	Tolerance Limits, Lower: 70 90 Upper:

Position No.	No. of Tests	Average $\bar{X}$	95% Conf. Limits for $\bar{X}$	Std. Dev. σ Inherent Error
1	10	83.2	± 0.4	0.641
2	10	83.5		
3	10	84.5		
4				
5				
6				
7				
8				
9				
10				

Total variability (6σ sp) is 5.48. $\frac{6\sigma \text{ sp}}{\text{Tol.}}$ = 5.48/20 = 27.4 %.
Positions (~~are~~ - are not) satisfactorily correlated.

Position to Position variability contributes 29.8 % to total variability. If it could be eliminated, the remaining variability would be 3.844/20 = 19.2 % of the tolerance. This (would - ~~would not~~) be satisfactory.



COMMENTS:

Quality Control Engineering

Fig. 2.

used for maintaining correlation control of test stations on a daily basis. This control is accomplished by converting the appropriate standard deviation into an upper control limit for the range of n independent readings. If the stations have been shown in correlation, the σ_{sp} is used to compute the maximum allowable range. If the stations were shown to be out of correlation, the σ_{un} is used to obtain the maximum range until the stations have been brought into correlation.

Each 24-hour period a production unit is run through all test stations, and the variables for the stations are recorded on the Daily Sidewinder Correlation Sheet. For each variable, the range of the n stations is computed and compared with the upper control limit allowed. If a range value is "out of control," corrective action is taken immediately. If all ranges are less than the upper control limit, testing continues because there is no evidence that the stations have dropped out of correlation.

By use of daily control testing of a production unit, confidence is maintained in the test equipment, and unnecessary adjustment is avoided.

CONCLUSIONS

The correlation-capability program has improved quality by permitting the establishment and maintenance of close correlation of test stations. Further, the span plan as an integral part of this program has shown itself to be a simple procedure involving a minimum of computation time.

By use of the gray zone technique, better control has been established over lower-order assemblies, resulting in an improvement in the ultimate quality of Sidewinder.

And finally, more uniform quality also has been assured through a daily check of each test station's correlation.

REFERENCES

[1] L. Seder and D. Cowan, "The Span Plan Method Process Capability Analysis," American Society for Quality Control, Milwaukee, Wis., General Publication No. 3; 1956.

[2] "ASTM Manual on Quality Control of Materials," American Society for Testing Materials, Philadelphia, Pa., Special Technical Publication 15-C, p. 43, Table II; January, 1951.

Built-In Reliability

E. P. LAFFIE[†]

INTRODUCTION

There has been a growing tendency, lately, to substitute the word "reliability" for "quality control." There have been many definitions for reliability proposed. A simple but adequate one has been given by Knight, et al.: "The reliability of an electronic product is the probability that the product will give satisfactory performance for a given period of time when used in the manner and for the purpose intended."[1]

One of the basic and fundamental concepts for achievement of true reliability is to build the product right in the first place. The aim of this paper is to point out how this can be accomplished and areas of actual application.

APPROACHES

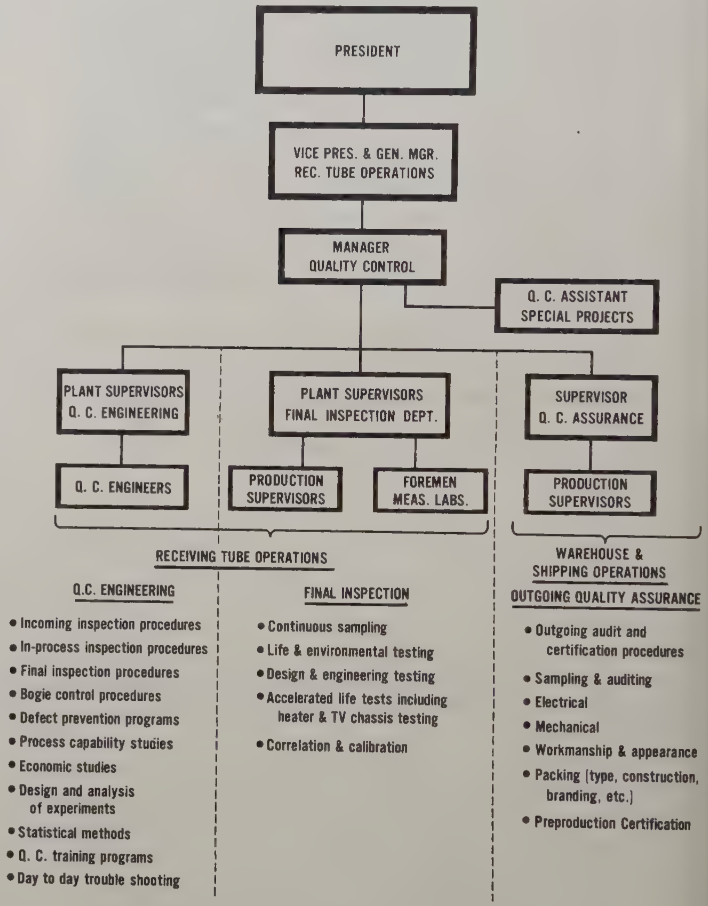
The subject for today is "Built-In Reliability".

One of the best approaches to total reliability is by coordinating the efforts of production, engineering and quality control groups.

The stronger position the quality control group has in the organization, the more assurance there is that a reliability program will be successful. Refer to the quality control organization chart attached. (See Fig. 1.) Note that the Quality Control Manager has an autonomous position in the company. He reports directly to the Vice President and General Manager of operations so that he is not unduly influenced by pressure of manufacturing schedules. He is directly responsible to high authority independent of production and engineering influence for the unquestionable quality of the outgoing product.

Another productive and rewarding approach to reliability lies in continuous analyses and evaluation of rejects. Productive areas include the following:

1) Rejects found by your own inspection departments.



ORGANIZATIONAL CHART

Fig. 1.

2) Rejects found in life testing the product.
3) Life test rejects found and returned by customers.
4) Line and Field rejects found and returned by customers.

Experience has shown, on the average, that approximately 50 per cent of all returns on receiving tubes are good by all existing precise measurement standards. Of the 50 per cent that are actually found bad, however, the major portion of these rejects are caused by poor workmanship

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† *CBS Electronics, Div. of Columbia Broadcasting System, Inc., Danvers, Mass.

[1] C. R. Knight, E. R. Jervis, and G. R. Herd, "The definition of terms in the study of reliability," IRE TRANS. ON RELIABILITY AND QUALITY CONTROL, vol. RQC 5, pp. 34-56; April, 1955.

attributed mainly to the human element. In other words, it was not made right in the first place and quite possibly the nonconforming parts cannot even be inspected out of the product efficiently.

One of the basic, but successful, approaches to this problem is by "Built-In Reliability"—minimizing or completely eliminating the problem or possibility of human error—prevention of rejects, rather than sorting. The problem no longer exists and, therefore, you do not have to depend on inspection as a crutch to remove the defective pieces.

AREAS OF APPLICATION

The following illustrations point out some of the successful approaches and concepts in action. Very little mention is made during this presentation of the application of statistical quality control techniques. Actually, considerable work was done in this area to prove the validity and success of these programs.

IMPROVED HEATER PROCESS METHODS

The "heater" in a receiving tube is often referred to as the "heart" of the tube. One of the problems associated with heater wire is the control of the diameter of insulating coating that is put on over the basic tungsten wire. This is necessary to control electrical characteristics and mechanical tolerance fits later on in the process of manufacture.

At one time, this control was strictly a hand control and the capability of the process was really at the mercy of the operator. (See Fig. 2.) Solutions to reduce the viscosity of the coating material were added by hand. O.D. measurements were made by the use of a hand micrometer and were subject to large degrees of inaccuracies. Fig. 2 clearly shows significant changes and assignable causes of variation. Actual process spread in this case was approximately ± .002".

The new method of diameter and viscosity control has resulted in a substantial improvement.[2] (See Fig. 3.) Note the marked improvement in process capability. Actual process spread is now approximately ± .00015". This new method allows continuous production of 24 hours per day over the old method of numerous stops and starts. The

[2]Details of this new method are described in "Photocell Gages Improve Tube Filaments 10 Times," in "Control Engineering—1959," McGraw-Hill Book Co., Inc., New York, N. Y.

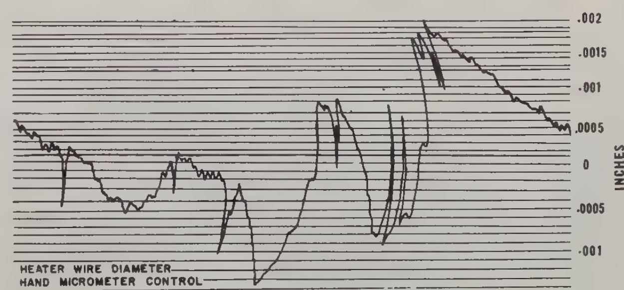


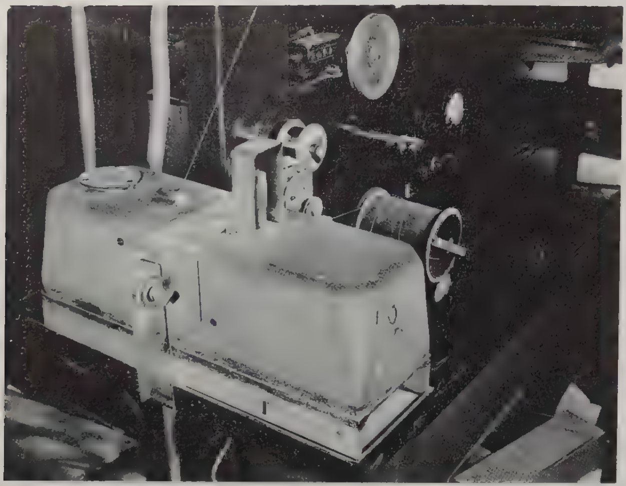
Fig. 2.

solution is now diluted automatically. Outside diameters and density of coating are now measured by means of photoelectric gages and are now held to tolerances of 1/10 of that previously accepted.

Substantial improvements have been realized in productivity and built-in reliability.

RELOCATION AND RELIABILITY IMPROVEMENTS SPADE WOUND HEATERS

At one time, spade wound heaters were folded, sheared and stored in a separate department from the mount assembly area. (See Fig. 4.) These heaters are removed from the machine and individually placed in appropriate holes in special circular trays for transportation to the mount assembly department which is located in another area. This machine is operated in production at a comparatively rapid rate of speed due to the pressure of meeting production schedules. This imparts a whipping action to the heaters being wound. This may distort the heaters and cause fragmentation of the basic wire and/or excessive amounts of insulating coating to be broken off at the apices.



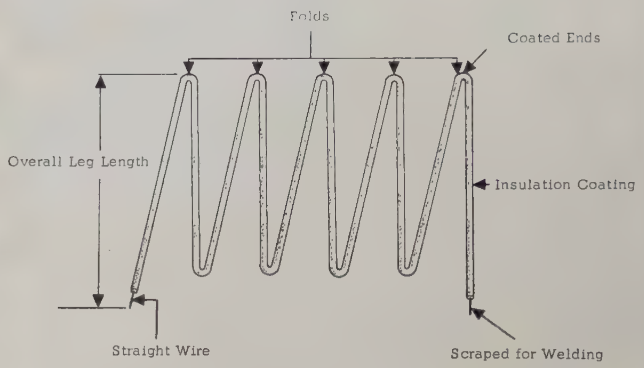


Fig. 5.

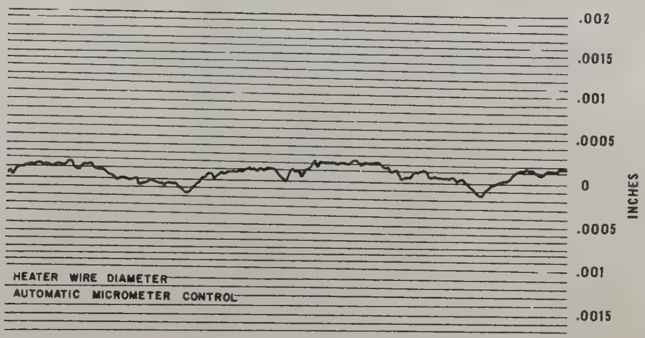


Fig. 3.

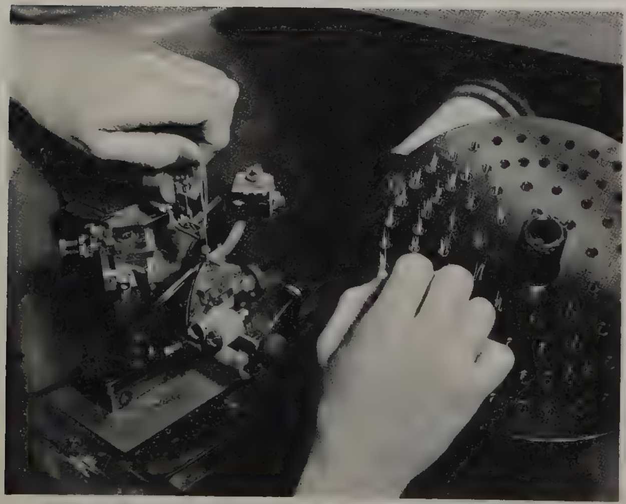


Fig. 4.

See Fig. 5 for a description of an individual heater.

After transportation to the mount assembly department, it was necessary for each mount operator to remove individual heaters from the trays for insertion into the mount. See Fig. 6.

Fig. 6.

This system was modified by relocating the spade winding machines in the mount assembly area. See Figs. 7 and 8. The operator was then able to make her own heater, on her own machine, at a slower rate of speed. The operator was also able to take the finished heater directly off the machine and insert it into the mount.

Advantages of this new method:

1) Reduction in the degree of human element.
2) Pride of workmanship—operator is now making her own part.
3) She can no longer find fault with the preceding department's work.
4) 5 to 1 reduction in machine speed at the new operation. The operator is now interested in making one good unit at a time. She no longer has the production pressure of lots or numbers of units.

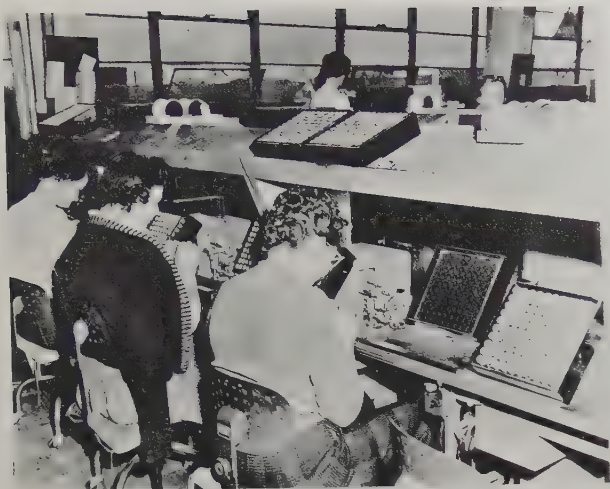


Fig. 7.

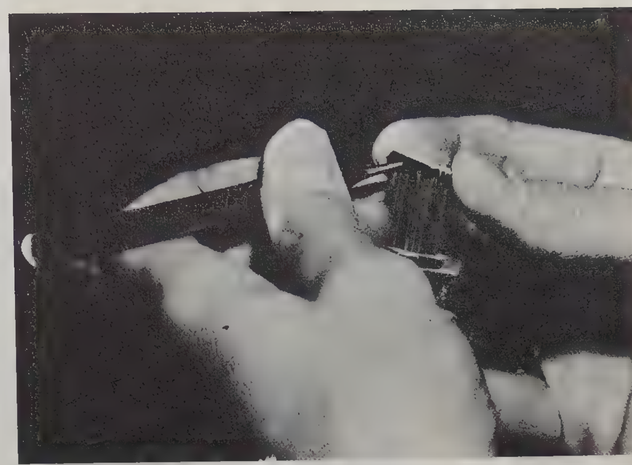


Fig. 9.

Fig. 8.

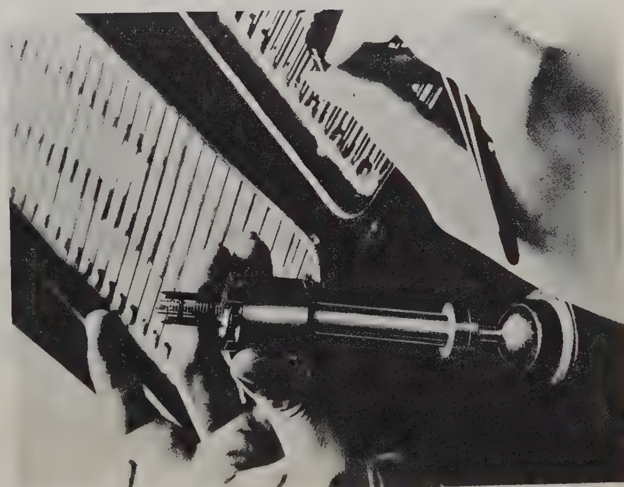


Fig. 9–A.

5) Less handling and transportation.
6) Increased productivity, less waste and increased reliability.

SEMI-AUTOMATIC MOUNTING VS HAND MOUNTING

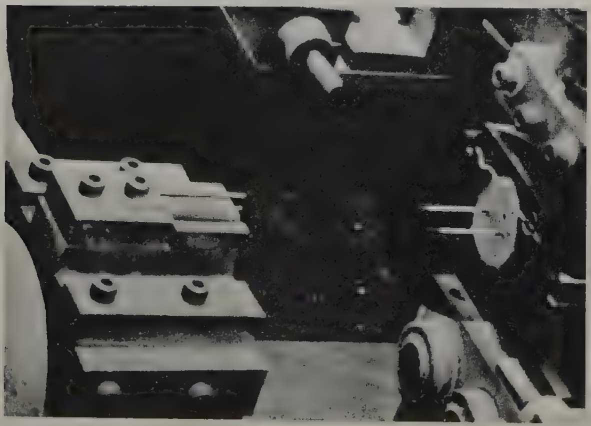
Hand Mounting Operation: A simple hand mount-jig was used to minimize human error at one time. Even though the jig provided in-tolerance guide holes and pins, it was still necessary for the operator to perform a considerable amount of hand manipulations. See Figs. 9 and 9-A.

This system is being replaced by semi-automatic production aids which eliminates much of the human error.

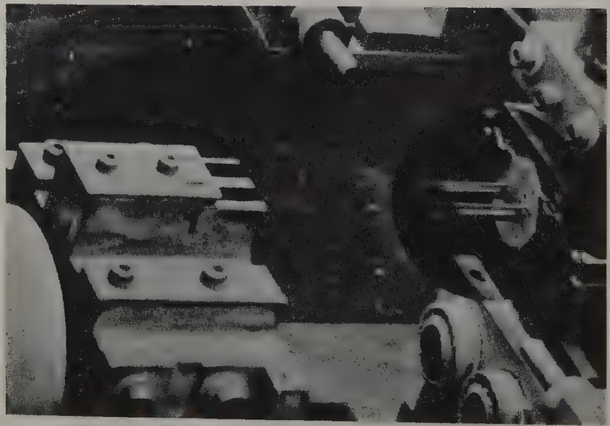
Semi-Automatic Production Aid: An equipment improvement group is continually engaged in observing current techniques for possible improvements. As a result of the group's effort, several processes have been modified so that they eliminate human contact with the parts used in vacuum-tube manufacturing. One of the improved processes is the semi-automatic production aid. With an aim toward minimizing the human error factor, several semi-automatic mount aids are being used in production lines. The step-by-step procedure is pictorially shown in Fig. 10.

Fig. 10.

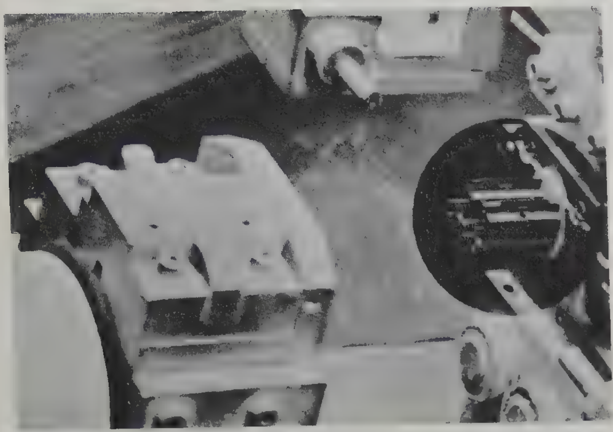
The semi-automatic mount aid illustrated here is designed to appreciably reduce the human error factor. Its precision action and alignment mean greater consistency to insure mount quality.



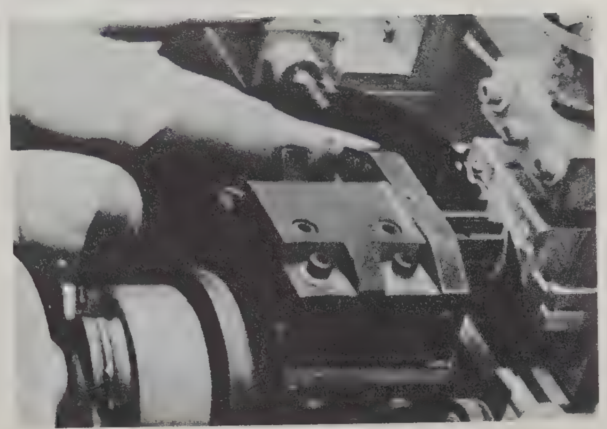
Using tweezers, the operator places the mica disc on the headstock. The cathodes, placed in the carriage, are automatically aligned with the mica holes. The carriage moves forward, inserts the cathodes, and is indexed to the next position on its return stroke.



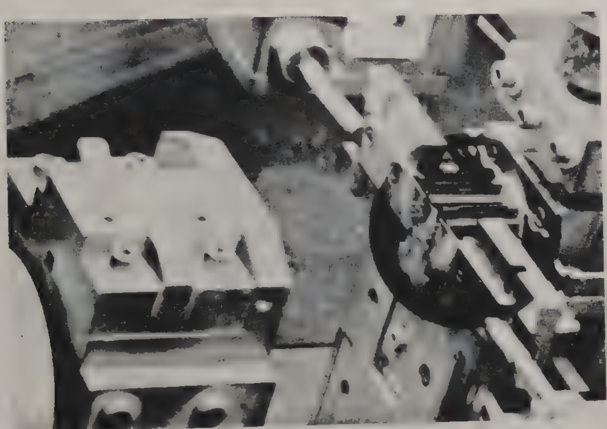
The second step places the grid legs into the mica holes. The chuck, located on the carriage, is indexed at the completion of each step.



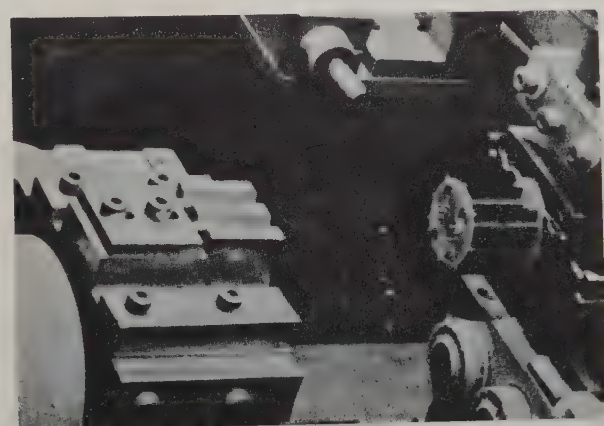
The plates fit over the grids. Proper mica dimensions hold each part tightly in a horizontal position. The parts cannot droop or come in contact with each other.



The plate ears are bent over the top mica to hold the mount rigidly together.

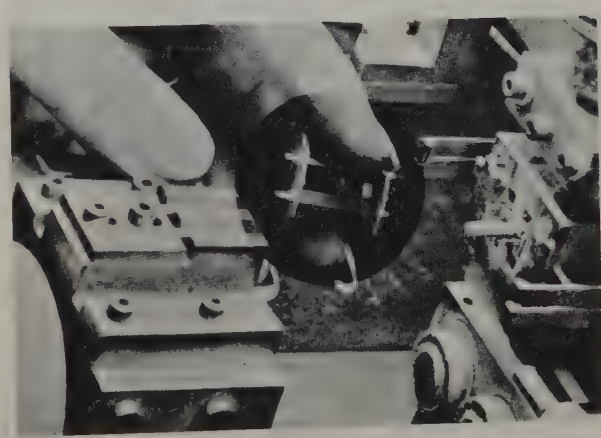


Although near perfect alignment is made as each part is installed, machined fingers snap into place to compensate for even the finest possible deviation from the specified tolerances.



With the carriage and chuck returned to its initial condition, the mount is now ready for removal.

As the first part mount assembly nears completion, the top mica is placed on the chuck.



Once the mount is removed the machine is ready for another cycle to begin.

The finished mount is placed into a pre-molded tray for delivery to the next stage of production. (Note: Rubber finger coverings, normally worn in production, were removed for this series of photographs so as not to obscure the details.)

THE QUALITY MAN'S DREAM

Only in-tolerance parts get through. The parts must be made and controlled in the previous feeder department or they will not "go." (See Fig. 11.)

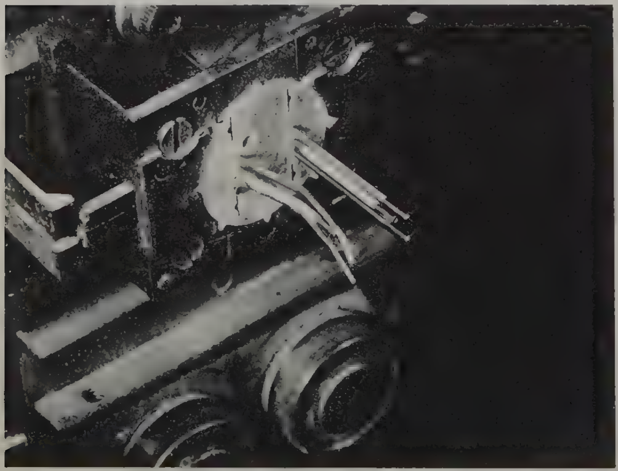


Fig. 11.

AUTOMATIC TEST EQUIPMENT

An unique automatic testing instrument is used in our production areas which has aided in obtaining total reliability. A panoramic view of the console reveals a masterpiece of precision engineering. (See Fig. 12.) This console is capable of testing many types by a simple programming technique.

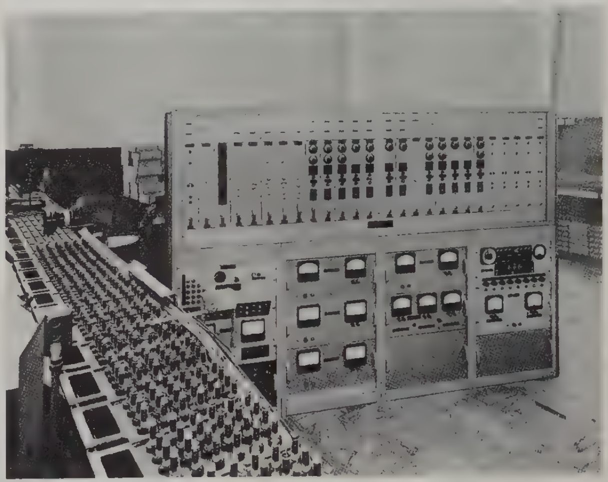


Fig. 12.

CONVENTIONAL TESTING

It takes two operators to test tubes coming from one aging conveyor. This is a highly skilled operation allowing for too much human error. The operator must manipulate successive switches in correct sequence. Alertness, fatigue, etc., play a large part in the efficiency of this type testing operation.

The new automatic testing instrument is fully automated. From the time the tubes are fed on to the conveyor belt to the completion of the testing program, the testing and evaluation is performed by this console without the aid of an operator. The conveyor belt is sequentially indexed to each test module. For each tube characteristic to be checked, there is a module especially designed and calibrated to the limits required.

As the tubes move along the unit, counters register the number and type of failures. The tubes that fail are immediately ejected into bins which are separated into failure categories. (See Fig. 13.) Notice that these bins with the black knobs at the bottom of Fig. 13 are not very large in volume. As tubes begin to fail, these bins fill up rapidly. If the problem is not solved quickly, or the process shut down, the doors of the bins open and the rejected tubes roll out on to the production floor. This has a tendency to force quick corrective action. Several times daily the failed tubes are returned to the quality control group for analysis and evaluation. Their findings are fed

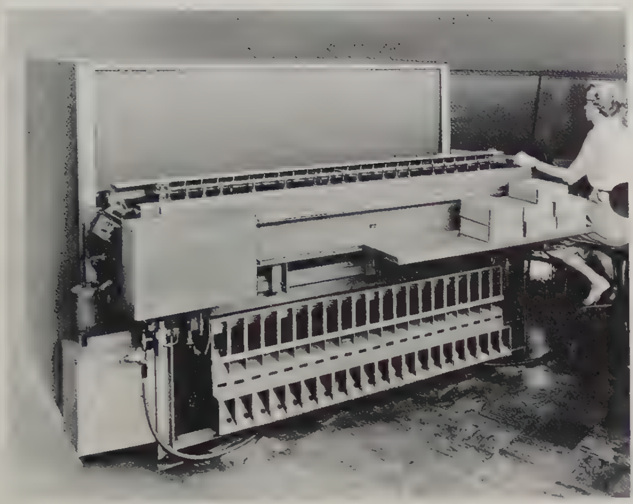


Fig. 13.

back to engineering for incorporation into the product improvement program.

Visual aids in the form of indicator lights and meters are an operating part of the equipment which continuously monitor the many conditions of the test. All operating voltages are regulated to insure maximum accuracy. The automatic test instruments are frequently checked and calibrated to assure maximum product quality and reliability.

Other slides presented but not illustrated in this paper are as follows:

1) Old and new method of cutting and bending miniature buttons.
   Advantages—a) Elimination of the human element by automation.
   b) Less handling by automatic packaging.
   c) Less production down time.
   d) Less and more routine maintenance possible.
2) New method of coil heater insertion into mounts.
   Advantages—a) Untouched by human hands.
   b) More uniform positioning of part for welding.
3) Accelerated Life tests and its contribution to reliability.
   Advantages—a) Information from the test has led to design and process changes for better reliability.
   b) Typical defects found and actual analyses performed were illustrated.
4) Reliability ratings at the customer—"proof of the pudding" that built-in reliability pays off at the customer in terms of incoming inspection, line, life and field rejects. Illustrations and method of numerous customer ratings were given.

Contributors

William D. Ashcraft (S'55-M'56) received the B. E. E. degree from Clemson College, Clemson, S. C., and the M. S. E. E. degree from the University of Pennsylvania, Philadelphia.

He joined Autonetics in 1956. He has served as Senior Engineer in the development of stellar portions of inertial navigation systems, and is presently a Senior Staff Engineer in the Electromechanical Systems Department of the Inertial Navigation Division of Autonetics in Downey, Calif. For the past year and a half, he has been engaged in originating criteria, concepts, and technology for computer-aided development and design of electronic and electromechanical systems and components.

Mr. Ashcraft is the holder of three patents.

Harry C. Bartels (A'54-M'59) was born on July 31, 1920, in Philadelphia, Pa. He received the B. S. degree in electrical engineering from Drexel Institute of Technology, Philadelphia, in 1948, and the M. S. degree in 1956.

During World War II, he was a pilot in the U. S. Air Force, and served in Italy with the 15th Air Force. He has been employed by the Philco Corporation since 1948, as an engineer, and subsequently as Manager, Quality Control.

Mr. Bartels is a member of Eta Kappa Nu, Tau Beta Pi, and Phi Kappa Phi honor societies, and is a member of the American Society for Quality Control.

Howard Berke (M'61) was graduated from Rensselaer Polytechnic Institute, Troy, N. Y. He worked as a process development engineer and as a sales engineer before joining the General Electric Company in 1952. In 1956 he was employed by the company's Light Military Electronics Department in Utica, N. Y., and is now Supervisor of the quality control function for one of the product areas of the Department. In this capacity he has had extensive experience with quality control programs for several important military weapons systems.

Mr. Berke is a licensed professional engineer and a member of Tau Beta Pi and Pi Tau Sigma honorary societies.

Thomas W. Gross (M'58) was graduated in 1956 from the University of Arizona, Tuscon, with the B. S. E. E. degree. He then joined Convair, where he assumed the responsibility of instigating a program for evaluating environmental effects on electronic component parts used in the Convair 880, F-102, F-106, and the Atlas programs.

In 1958 he joined Lockheed Aircraft Corporation to work on the satellite programs as a Senior Reliability Engineer. He is primarily concerned with passive electronic parts and the data interchange program.

Walter Hochwald (SM'56) received the B. S. E. E. degree from Pacific States University, Forest Grove, Ore., and has completed thirty-four semester units of graduate work at the University of California at Los Angeles and the University of Southern California, Los Angeles.

He has been with Autonetics since 1948, and presently heads a staff group of engineers in the Electromechanical Systems Department of the Inertial Navigation Division in Downey, Calif. For the past year and a half, this group has been engaged in originating technology and implementing organizational concepts for computer-aided development and design of electronic and electromechanical systems and components. Prior to his present assignment he served as Supervisor of a Research Unit engated in development of airborne precision digital-to-analog converters.

Mr. Hochwald is the holder of seven patents and is a member of the National Management Association. He is the author of several technical papers on transistor dc amplifiers and of a portion of the "Computer Handbook," published by the McGraw-Hill Book Company, Inc.

Edward P. Laffie received the B. S. in B. A. degree from Boston University, Boston, Mass., in 1939. From 1939-1949 he was with Sylvania Electric Products.

In 1949 he joined CBS Electronics, Division of the Columbia Broadcasting System, Inc. He has served in the capacities of Quality Control Engineer (receiving tubes); Quality Control Supervisor (receiving tubes and semiconductors); Staff

Director of Quality Control (receiving tubes, picture tubes, and semiconductors); Manager of Quality Control Line and Staff (receiving tubes and semiconductors).

Mr. Laffie is a member of the Boston Section of the American Society for Quality Control.

Charles B. Tague (S'50-A'51-M'56) was born on April 16, 1924, in Pleasantville, N. J. He received the B. S. degree in electrical engineering from Drexel Institute of Technology, Philadelphia, Pa., in June, 1951, and has done graduate work in business administration at Temple University, Philadelphia. During World War II he served with the Third Army overseas.

Mr. Tague joined the Philco Corporation, Lansdale Division, in 1948 while still attending Drexel. Since graduation he has worked two years in production engineering in receiving tubes, five years as project leader on special tubes, one year in transistor development, and three years in transistor manufacturing. He is presently Manager of the Lansdale Germanium Transistor Manufacturing Facility.

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